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FIRE-RES

Innovative technologies & socio-ecological-economic solutions for fire resilient territories in Europe

D1.1 TRANSFER OF LESSONS LEARNED ON EXTREME WILDFIRE EVENTS TO KEY STAKEHOLDERS

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Abstract:

This framework outlines the pillars and key concepts of the FIRE-RES project work packages (WPs). It also translates the framework into a set of guidelines in the form of unresolved challenges that need to be addressed in order to create resilient landscapes in front of Extreme Wildfire Events (EWEs).

These challenges define the path for technological, social, ecological and economic innovative solutions to be developed in different FIRE-RES WPs.

The **concepts** *extreme* and *resilient* are often open to multiple interpretations. Depending on the area from which they are drawn or analysed, nuances may appear. For this reason, this deliverable addresses these concepts without aiming to find an agreed definition, but only to allow all partners to have the same vision of what we are facing in the project. During the course of the project, it may be possible to clarify aspects that cannot be covered in as much detail in this initial framework.

We have now **learned lessons** from different wildfire events, especially from Pedrógão Grande Fire. This is a relevant case for this project as it happened within the EU borders and many of the challenges it raised are still unresolved. How come the fire behaved the way it did? Would we be able to foresee and successfully manage that situation if it were to happen again? Analysing this case is an opportunity to understand EWEs and to create resilient landscapes.

The main **challenges** faced by the emergency and fire management are related to communication, interoperability, training, uncertainty, and lack of capacity to monitor and predict EWEs.

The **concept of resilience** has evolved significantly over the past few years, resulting in a variety of terminologies and approaches: from recovery to its initial state, the traditional approach; to adapt or transform to a new state according to ongoing climate change.

The main challenges for achieving **resilient landscapes** in the context of EWEs are linked to different topics. From the ecological and landscape management point of view, they are linked to the available fine fuel loads, to the need of fuel treatments focused on reducing damage rather than the extent of EWE, or to the restoration treatments. When approaching the fire as a management tool, it becomes important to deal with traditional burning, prescribed burning, and wildland fire use. Equally important is the inclusion of economic aspects of resilient landscapes. Finally, from the governance and risk awareness perspective, various aspects are highlighted, such as Land Use and Land Cover (LULC) data and burned area data to analyse the territory, or aspects linked to the participation of stakeholders from local communities, both private and public.

At FIRE-RES, we aim to develop an operational methodology that considers multiple dimensions (e.g., environmental, social, economic) to provide an integrated assessment of fire resilient landscapes, since most approaches focus solely on one dimension. This methodology will allow the identification of strengths and priorities in each landscape to be resilient to EWE and show where classic, adaptive, or transformative resilience should be promoted.

This framework cannot address every question that may be raised. As a framework, it only provides an **overview of the way forward** and it will be up to the different work packages (WPs), Innovation Actions (IAs) and tasks to go into details. Many questions will remain unanswered, and this is the very first step: asking questions about where to invest efforts to find solutions to the challenges ahead. The FIRE-RES project will contribute to solving some of the existing issues, as this is where the innovation for creating resilient landscapes will be found.

Key words: extreme wildfire event, resilient landscapes, uncertainty, lessons learned, challenges

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Introduction

Extreme Wildfire Events (EWEs) could cause the collapse of some systems in Europe, resulting in crises at multiple levels: environmental, socioeconomic, and civil security. If we consider the size of the European continent, being able to recover from collapse necessarily requires landscapes capable of absorbing disruptions (resilient landscapes) and adapting to new situations after the changes. To avoid this breakdown, it is necessary to consider environmental (including humans and disruptions as part of the system) and socio-economic factors must be considered in the management cycle phases, as well as all actors' perspectives and relationships.

FIRE-RES aims to provide the EU with the ability to avoid collapse in front of EWEs by accelerating the socio-technological transition by integrating environmental, climate, health & safety/security, cultural, and socio-economic factors through the development of innovative actions. This goal is becoming relevant since EWE are projected to increase under forecasted harder climate conditions.

There is broad consensus that in order to increase our resilience, we must change the model of dealing with forest fires that Europe currently employs. The existing European model (which is based, among other things, on large investments in trucks and air resources, and understanding fire as something that must always be extinguished regardless of the type of fire, etc.), will not further succeed at facing the change of extreme regime that is taking place. But to update the model, it is needed to first clarify the principles that will be presented next.

One of them is to define a basic terminology between the partners of the project. We tried to reach an agreement in defining *extreme wildfire events* and *fire impacts*. It is also essential to describe possible future scenarios since it is necessary to decide and to calculate the options available and follow the road to avoid future disasters. Scenarios allow managers to better comprehend uncertainties and consequently make robust decisions under a wide range of possibilities. Moreover, it is crucial to monitor "actions" and their impacts to determine which of them bring us closer to the desired scenarios or further away from them.

There are agents that have the capacity to control key elements of the landscapes. The decisions of these agents/actors based on their responsibilities and agreements will define the future scenario. So, it is vital to integrate the social perspective and the different actors who have the capacity to influence in this future scenario as their actions will facilitate or hinder tackling the change, and this also entails responsibilities. Therefore, the common interest will also need to be agreed. In addition, to address these situations is important to look to those innovative hubs that analyse actual scenarios and collect lessons learned to adopt a new way to take decisions based on this knowledge and more generally a new way to think (e.g., a new Incident Command System (ICS) adapted to the lessons learned).

One of these agents considered a hub with control of various key elements is the response sector for different reasons:

1. Emergencies are increasing in complexity faster than our capacity to innovate. **These new challenges foster innovation because those who face new situations usually need to innovate to overcome them**, but it needs time to develop and disseminate them. In addition, the information age has also changed the structure of knowledge and decision-making. (FIREIN D1.4, 2021).
2. **Few wildfires have been identified as EWEs worldwide to date and few have experienced these directly**. Emergencies are a source of knowledge and responders frequently need to be creative and innovative when facing new challenges created by new emergencies. But responders cannot obtain all of the essential existing knowledge to deal with EWEs as quickly as events occur, nor can they gain direct on-field experience in these EWEs at the same time. Organizations, on the other hand, can transfer knowledge and bridge the gap between the individual and collective scope by using appropriate "knowledge cycles" (Miralles, M. et al, 2021). Responders have data and direct observations that are difficult to obtain, and researchers have the ability to analyse and provide answers. As a result, **teamwork is needed to find answers and solutions**.

Aim of the deliverable

The FIRE-RES project includes many different actors, fields of expertise and areas. This is of significant value and adds value to the project results. However, it is fundamental to build a standard initial framework to ensure that all work packages begin conceptually from the same point. FIRE-RES intends to introduce new innovations, so it is essential to address the difficulties that remain unresolved today and invest in these gaps.

It is also important to bear in mind that the realities in each country and in each organization may differ, so the work in this first phase of the project aims to find the same starting point to work from, to assess what is innovative or existent (equally important but outside of the focus of the EWE context) and to encourage the promotion of those innovations that truly respond to the identified challenges and existing gaps.

The purpose of this report (D1.1) is to provide a framework for the FIRE-RES project to facilitate a common vision to tackle the EWE. The first step is to examine at the phenomena in order to address what needs to be faced with the innovation and resilience proposed in this project. Therefore, it is of paramount importance to address the process, particularly its behaviour and drivers (fuel in the ecosystem (t/ha), atmosphere, energy emission (kW/t), etc.).

This deliverable includes the outputs of the initial workshops (WS) developed to create the project framework and the thematic lines that will guide the project's WP (Task 1.1, WP1). These workshops took place at the beginning of the project and covered the project pillars: (i) EWE process/behaviour drivers: fuel in the ecosystem (t/ha), atmosphere, energy emission (kW/t), to support WP5; (ii) emergency and fire management, to support

WP2, WP4, WP5; (iii) landscape and economy, to support WP2-WP4; and (iv) governance, society, communication and risk awareness, to support WP4 and WP7.

Two different workshops were organized to raise awareness about the dimensions, characteristics, best practices (BP), lessons learned and current knowledge of the EWE.

The first workshop (WS1) aimed to draw on genuine EWE cases and learn about *how* they happened, best practices and lessons learned, and the challenges and questions they raised by gathering information from those who experienced these situations. This workshop focused on the pillars (i) EWE process/behaviour drivers and (ii) emergency and fire management.

The goal of the second workshop (WS2) was to reach a common understanding (or even a working definition) of what "fire resilient landscapes" are. The idea was to identify lessons learned from many perspectives on this notion and to broadly outline the difficulties of developing resilient landscapes to wildfires and EWE. This workshop approached the pillars (iii) landscape and economy and (iv) governance, society, communication, and risk awareness through approaching four topics: ecology and landscape management (topic 1), fire as a management tool (topic 2), economic aspects of resilient landscapes (topic 3) and governance and risk awareness (topic 4).

These introductory workshops had the aim to demonstrate the various issues that the responding agencies and land managers are currently confronting. From these challenges, the different IAs and tasks of the project will offer solutions to approach them. **As a consequence, in order to serve as a guide for future Innovation Actions, this document addresses the issues that exist today in dealing with EWE**.

During the WS, various experts, project partners and Working Package Leaders (WPL) had the opportunity to discuss in an integrative and transversal manner, detecting connections, strengths and weaknesses of the proposals made, improving them as much as possible, and identifying guidelines from real cases.

The following are the specific objectives of this deliverable:

1. **Develop a framework**. The FIRE-RES partnership is broad, with actors with diverse expertise, experiences, targets and demands. However, in order to cope with EWE, it is necessary to have a clear and shared vision of the phenomenon, landscape, processes, etc. we are facing, combining different perspectives while allowing us to move in the same direction to avoid collapse in the face of EWE.
2. **Establish guidelines**. Although the EWE phenomenon is the same throughout Europe, different regions have different realities, experiences coping with it, and demands. Those with minimal experience dealing with wildfires may see new solutions or methods that have already been tried elsewhere but may have a novel implementation, which may or may not be successful. Knowledge transfer is extremely valuable. Lessons learned and good practices can help to accelerate resilience and prevent collapse.

3. **Focus on finding innovations for EWE**. Due to a lack of expertise with wildfires in general, some regions may collapse in the face of EWE. But this does not mean that there are no solutions, methodologies, or ways of working that could help and that have already been applied in other fields. In other cases, the solutions discovered thus far have been highly suited for dealing with certain types of fires and respond to what has historically been needed to be addressed in each area, but they are ineffective for dealing with EWE. Therefore, what appears unique in particular circumstances may not be novel in a broader European context. In this project, it is important to focus on the real innovations that can make a difference, rather than just difficulties caused by a lack of knowledge transfer.

   We are dealing with an increase in the number of wildfires in areas that previously did not have them, as well as an increase in the size of wildfires, and thus reaction teams must face new conditions, even if they may be familiar from previous experiences. EWE is a new challenge with many associated uncertainties; therefore, innovations must focus on this global and extreme risk.

4. **Learn from EWE occurred in Europe**. Pedrógão Grande Fire (2017) was a wildfire considered extreme. Despite the fact that it occurred years ago (2017), there are still no answers to some questions that were generated. It is true that a lot of information was gathered and reports were made, but we still lack all of the required knowledge to establish why the phenomenon occurred. Answering this question is essential for dealing with comparable events. Furthermore, because this EWEs occurred in Europe where the FIRE-RES project is geographically contextualized, learning from this event is extremely significant. Other cases and examples, on the other hand, are appreciated because they increase the amount of cases to work with.

5. **Facilitate the final assessment in the project**. At the end of the project, this initial framework should be used to assess whether the innovations have served to fill the gaps and challenges, at least some of them, through the Innovation Actions (IA) developed.

The major outputs of WS1 and WS2 are compiled in this document. The structure of this document makes it easy to discover the main elements from each theme. It is not the aim of this deliverable to go into details but to define general lines, lessons learned and crucial information to be able to address in greater depth in the next steps of the project. The guidelines are established based on the definition of EWE, as well as the identification of issues posed by EWE that produce gaps that must be filled.

European context

During WS1, Tomas Artés Vivancos of the Joint Research Centre (JRC) of the European Commission gave a speech on *the Extreme Forest Fires data at EFFIS/GWIS, a monitoring* *perspective (GWIS/EFFIS Team. JRC E1 Disaster Management)* to present the European context regarding EWE. The following section describes the key points of his speech.

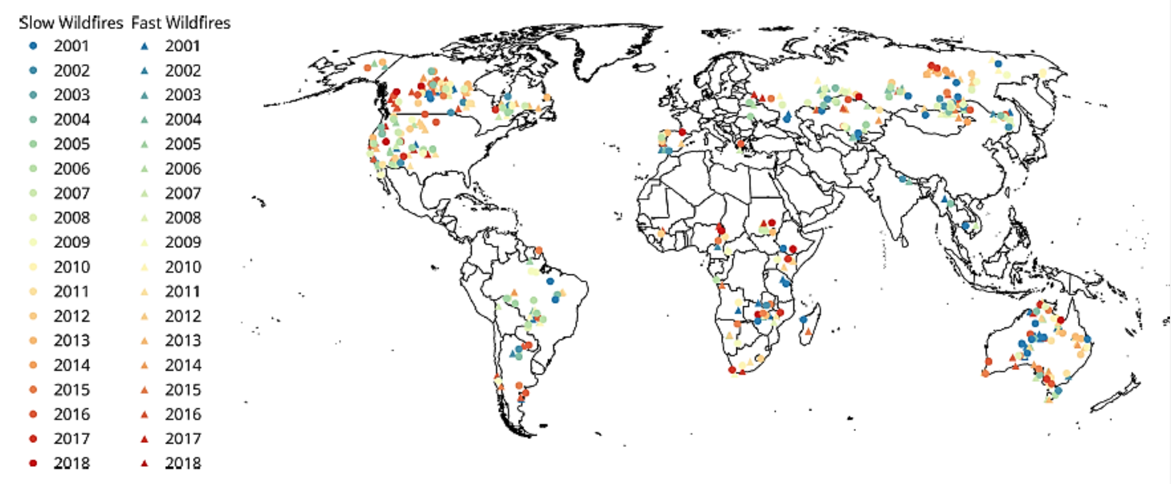

Fig. 1. Location of the wildfires coloured by year. Fast fires and slow fires are depicted with triangles and circles respectively. Selection of a total of 445 cases, with 223 fires larger than 10 000 ha and 222 fires smaller than 500 ha. Figure 1 shows the distribution and the year of each fire at the global scale [Artés et al., 2022].

- **From a monitoring point of view, developing a Europe-wide system appears appealing, but drawbacks must be considered.** It is interesting to have monitoring systems that go beyond simply comparing countries to one another, but more importantly, to have the same technique for the whole Europe. However, there are countries with a high number of small forest fires that may be overlooked while tackling EWE at the European level.

- **Since 2000, a new peak in the frequency of fires and burned area has arisen in various locations.** There are records values in terms of number of fires and the burned area. **During the last years this change has moved from south to the north of Europe**. It began in Mediterranean areas but has been observed moving north during the last 3–4 years.

Tests have been carried out to try to measure different parameters at European Scale e.g., the ability to collapse in front of an EWE:

- **The amount of burned area at European scale is not uniform across countries and does not clearly correspond to request for assistance:**

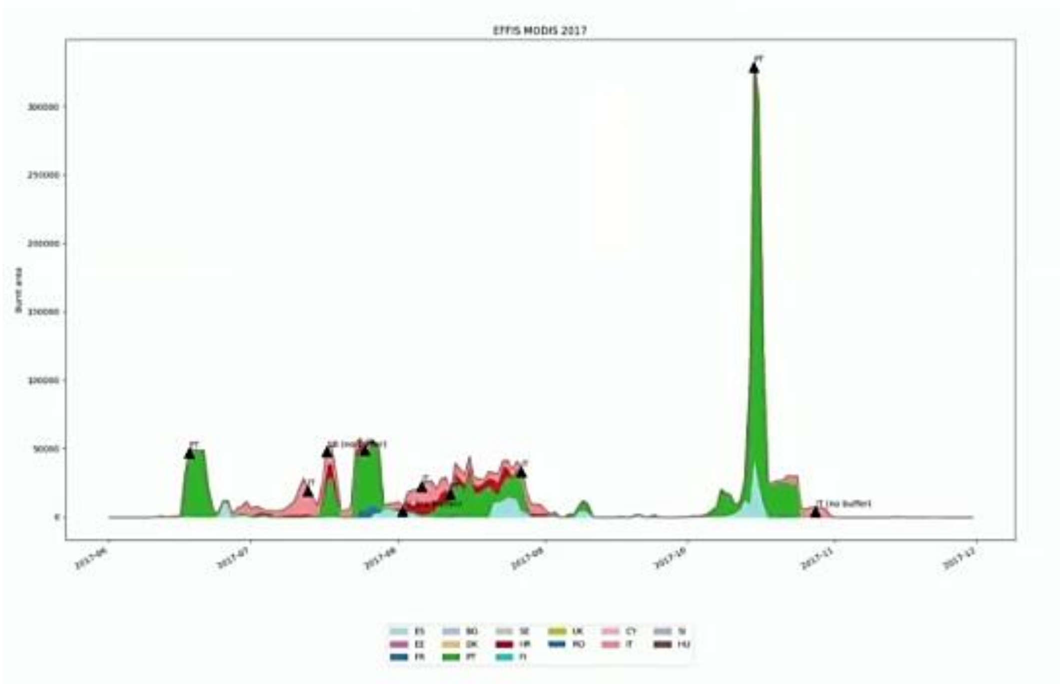

Fig. 2. Amount of burned area from EFFIS MODIS 2017 (European Forest Fire Information System, EFIS) per country. The plots were originally made on request, to see the relationship between activity and applications for aid between countries, to see if it was convenient for the EC to have its own resources. Data from: https://www.nature.com/articles/s41597-019-0312-2. Graphic showed by Tomas Artés (JRC) during FIRE-RES WS1 session.

- **It is difficult to anticipate the need for help because each country has a unique context, characteristics, kinds of situations and means.** However, having an indicator to answer this gap would be useful. Some tests have been conducted to identify an indicator that relates the number of fires or the fire size with the calls for help, but they are not directly related.

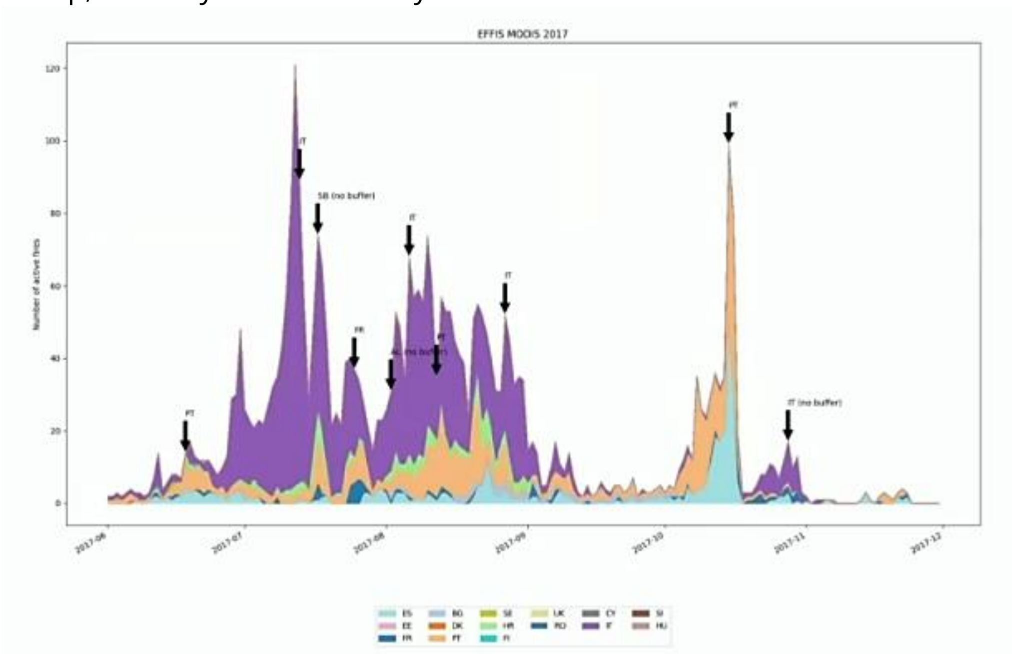

Fig. 3. Amount of burned area from EFFIS MODIS 2017 (European Forest Fire Information System, EFIS) to be compared with the calls for help. The plots were originally made on request, to see the relationship between activity and applications for aid between countries, to see if it was convenient for the EC to have its own resources. Data from: https://www.nature.com/articles/s41597-019-0312-2https://www.nature.com/articles/s41597-019-0312-2. Graphic showed by Tomas Artés (JRC) during FIRE-RES WS1 session.

In 2017, there was an attempt to identify when the countries had a request of collaboration or a request for help in terms of means inside the civil protection mechanism. Nonetheless, it also demonstrated that, in terms of burned area, the magnitude of the burned area was not directly related to calls for assistance. The amount of burned area showed significant differences and made evident that the result was not uniform at the European scale, on the contrary, it required an analysis at country level.

- **Tests have been carried out in order to obtain a vision of the danger at a global scale.** The global-scale analyses have focused on building a global database to provide a comprehensive overview of the hazard. Two climate data sources are currently used, ECMWF data and NASA Geos-5, but also Web Map Services (WMS). However, several issues have been detected. The application of the Fire Weather Index at a global scale or implemented in Europe is challenging, it is difficult to apply the same methods for all locations and occasionally simpler views are required to ease the implementation and there seem to be problems with time zones, particularly at midday.

- There are multiple ways to characterize global scale trends and anomalies:
  - ✓ **Fire weather Index[1] – ERA5 has been proved to be useful to detect anomalies at a global scale** using cases of fires in Australia 2019-2020 (https://zenodo.org/record/3269270#.YvJhFHZBw2w) .
  - ✓ **JRC tries to update all the fires at global scale four times per day at least using Terra products.** An algorithm has been developed to try to identify these fires that will later be inserted in a database.
  - ✓ GWIS Near-Real Time Wildfire data which is coarser than other types of data but useful to see fire trends in near real time.

- **Europe is among the ranking of the faster fires in the world:**

'*Figure 7 shows the fire density. This information identifies area with a high number of fires of a moderate average fire size (Fig. 8). For instance, focusing on Portugal, the number of fires is considerable higher in the north of the*

[1] The Fire Weather Index (FWI) is a numeric rating of fire intensity used as an index of fire danger in forests in Canada. It is based on other indexes as the Initial Spread Index (ISI) and the Build-up Index (BUI).

country. However, the average fire size is much higher in the central area of Portugal. See annotation a in Fig. 8. Then, it can be concluded that fires, on average, are bigger in the central part than in the northern area of Portugal. A similar situation is shown when comparing Madagascar with eastern Mozambique, annotation b. In this last case, it can be concluded that fires in Madagascar are sparser than in some areas of eastern Mozambique like around the Gilé National Reserve.

Since fires are individually located, some basic fire properties can be analysed for the events affecting each region. Recently, several works established the links between climate change and fires. In addition, the firefighting community noted that fires are getting more intense and harder to fight.

Figure 9 shows the maximum fire spread speed of those fires which affected a region. In Europe, the fastest moving fires occur in the south of Spain (b), in the Peloponnese (Greece, annotation c) and specially in central Portugal (b). From the global perspective, Santa Isabel (Argentina, annotation f), Malheur (USA, annotation a), Tableland (Australia, annotation h), Halhgol (Mongolia, annotation e), Chernozermel'skiy rayon (Russia, annotation d) and the Republic of Tanganika (g) have the fastest moving fires. Locations of the regions with fastest fire spread propagation match with the regions where wildfires were most unpredictable and harmful. In Europe, the central part of Portugal, south Spain and Greece stands out from the rest of Europe and matches with the most tragic fire events for this continent.'

Fragment of the article : Artés, T., Oom, D., de Rigo, D. et al. A global wildfire dataset for the analysis of fire regimes and fire behaviour. Sci Data 6, 296 (2019). https://doi.org/10.1038/s41597-019-0312-2. The article used data from 2001 to 2017.

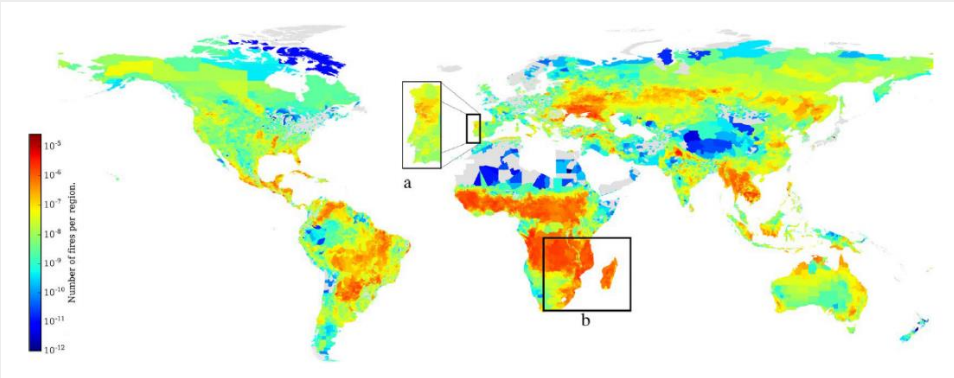

Fig. 7 Number of fires per region surface from 2001 to 2017.

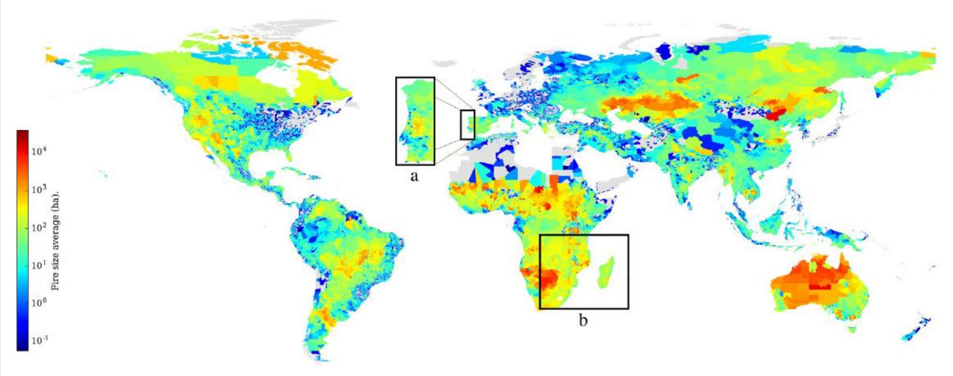

Fig. 8 Fire size average per region 2001 to 2017.

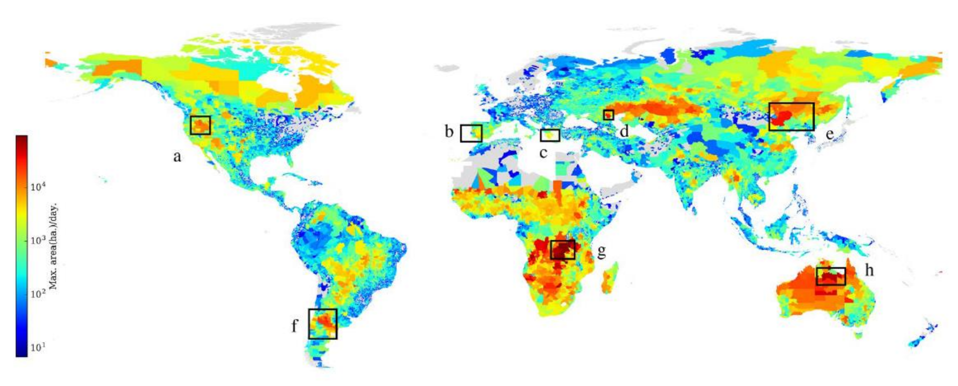

Fig. 9 Max. fire average fire spread per region from 2001 to 2017.

- **The temporal model indicates that there are more fires but with a smaller fire size.** Globally, there is a strong positive correlation between the number of fires and time (e.g., Artic areas or Northern Australia), but if the analysis is about the fire size, although there is still a strong and positive correlation, the average fire size tends to become smaller.

- According to data from 2000 to 2019, **the number of fires (especially the largest ones) and total burned area increased every year** in the Arctic, Australia, the Iberian Peninsula, and western Europe. Typically, there is a trend in the northern areas of more fires but less burned land, which could be attributed to fuel management or prescribed fire use.

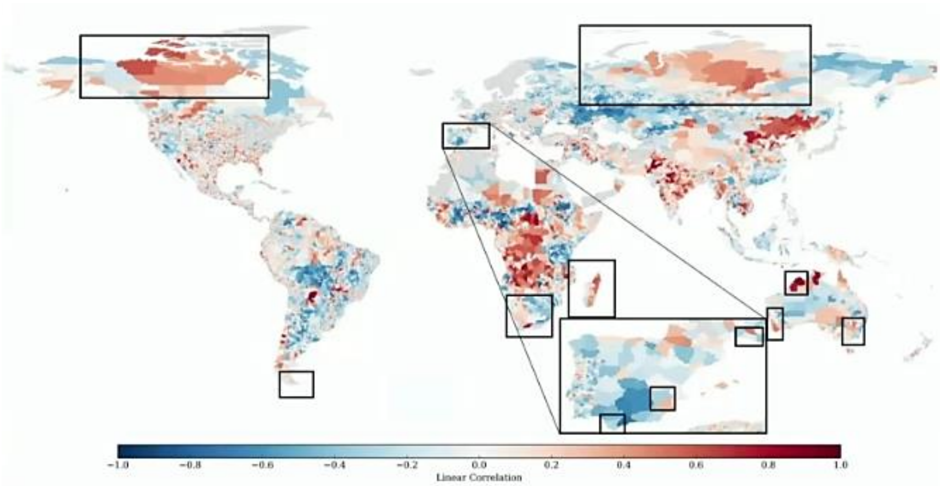

Fig. 4. Number of fires. Linear Correlation in Time. GWIS monitoring. Graphic showed by Tomas Artés (JRC) during FIRE-RES WS1.

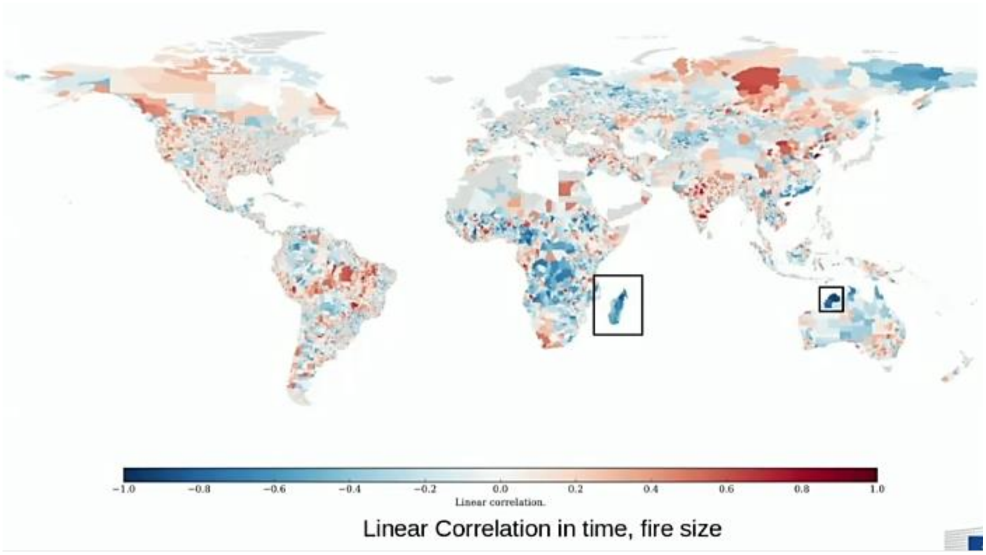

Fig. 5. Fire size. Linear Correlation in Time. GWIS monitoring. Graphic showed by Tomas Artés (JRC) during FIRE-RES WS1 session.

- **In some instances, when looking at monitoring systems, it can be difficult to discern what is going on in some cases** (Fig.4 and Fig.5), **thus additional parameters for fire events must also be utilized** interaction that has not yet been possible to integrate into the monitoring systems for the fires around the world.
  - ✓ Some fires behave in ways that are difficult to explain with the current knowledge and considering the classical parameters such as fire spread speeds. Some of its fire spread speeds are beyond the values provided by the current models.
  - ✓ When flames behave as EWE, it has been observed that computing a set of signals can produce considerable changes. See Fig. 6 from the Sala fire in Sweden in 2014 and Fig. 7 which shows the same kind of signals (example: CAPE, CIN, EFBI, CAPEP, TOTALE, TOTALEP, CINP) but in a map format and for Australia.

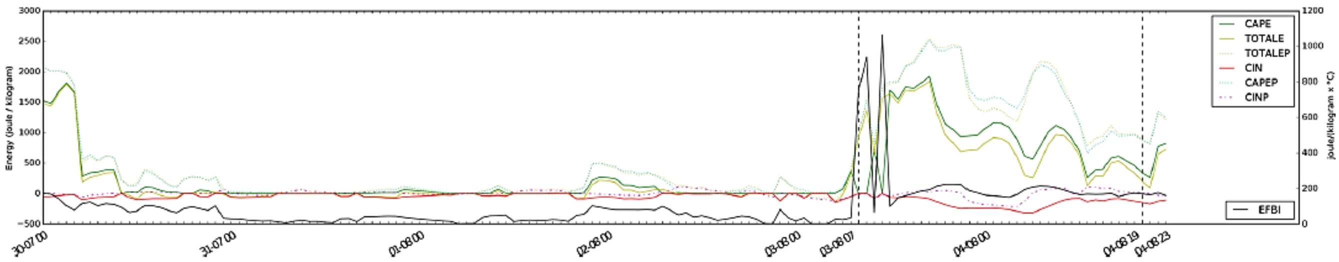

Fig. 6. Sample of the timeline of the Extreme-fire behaviour index, EFBI, (right vertical axis) and the factors used (left vertical axis) for the wildfire in Sala (2014, Sweden) that burnt close to 10 000 ha from 3 to 4 August 2014 (time period marked with vertical dashed lines). Horizontal axis is the timeline using hourly steps in the format dd-mm hh. TOTALE = CIN + CAPE. TOTALEP = CINP + CAPEP [Artés et al., 2022].

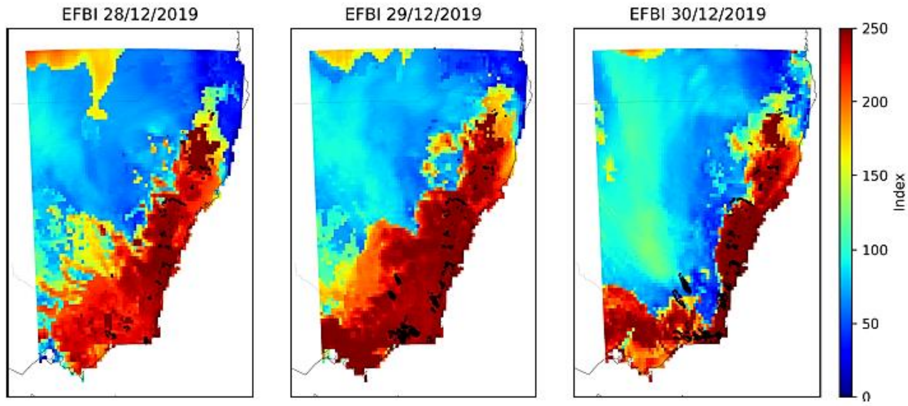

Fig. 7. The EFBI from 28 to 30 December 2019 overlapped with the active fires (black dots) that took place the next day over south-eastern Australia. Please note that the date format in this figure is dd/mm/yyyy [Artés et al., 2022].

- **The most significant case of EWE in Europe until the moment is Pedrógão Grande Fire:**

'Pedrógão Grande wildfire (Portugal, 2017) had one of the most severe fire behaviours in Europe. The fire was ignited on 17 June and ran until 23 June. Figure 8 shows an explosive expansion from 17 to 18 June, which is followed by a constant but severe fire expansion. For this analysis the fire perimeters made for a wildfire report done by a technical commission (Comissão Técnica Independente, 2017) were used as reference for the fire spread. From 17 to 18 June there was an increase of burnt area larger than 20 000 ha in one day.

Fig. 8 shows the value of the Extreme-fire behaviour index (EFBI) 5 reanalysis; the two vertical dashed lines in the figure delimit the duration of the fire. The Extreme-fire behaviour index, (EFBI) shows that there is a considerable potential for the interaction of the fire with the atmosphere. In addition, during the days of the fire there was a natural CAPE of nearly 5000 J kg−1 inhibited by a small value of CIN. Increasing the temperature at the surface, removing the inhibition, would produce a sudden convection. The index values are close to 250 J kg−1 ◦C −1 increase and a total convective energy about 6000 J kg^{-1}. ***This case shows a natural tendency towards a convection driven behaviour that may be caused by the atmospheric instability itself, without the need for a considerable amount of heat and/or an increase in relative humidity at the surface****. For this case study, detailed fire perimeters for each time step were available, which made it possible to analyse the relation between the maximum fire spread and the EFBI. Figure 8 shows a scatter plot where each point is a time step given an EFBI value and the estimated maximum fire speed. While a wide variety of values of the EFBI are shown for low fire spread speed values, considerably higher EFBI values are shown for high-speed values, compared with the rest of the point cloud. However, there is a weak correlation between the speed and the EFBI. It is worth mentioning that the blow-up of the wildfire took place at the beginning of the event; assuming that the fire was in convection almost from the first-time steps, the EFBI and fire spread speed may not show a strong correlation when looking at all the hourly time steps. However, Fig. 8 shows that, even with an ongoing convection driven fire, the atmosphere stability context computed from a numeric model is still important, and speeds faster 1 km h^{-1} are only present when the EFBI is above 220.'*

[Artés et al., 2022]

Note: ERA5: ECMWF Reanalysis v5

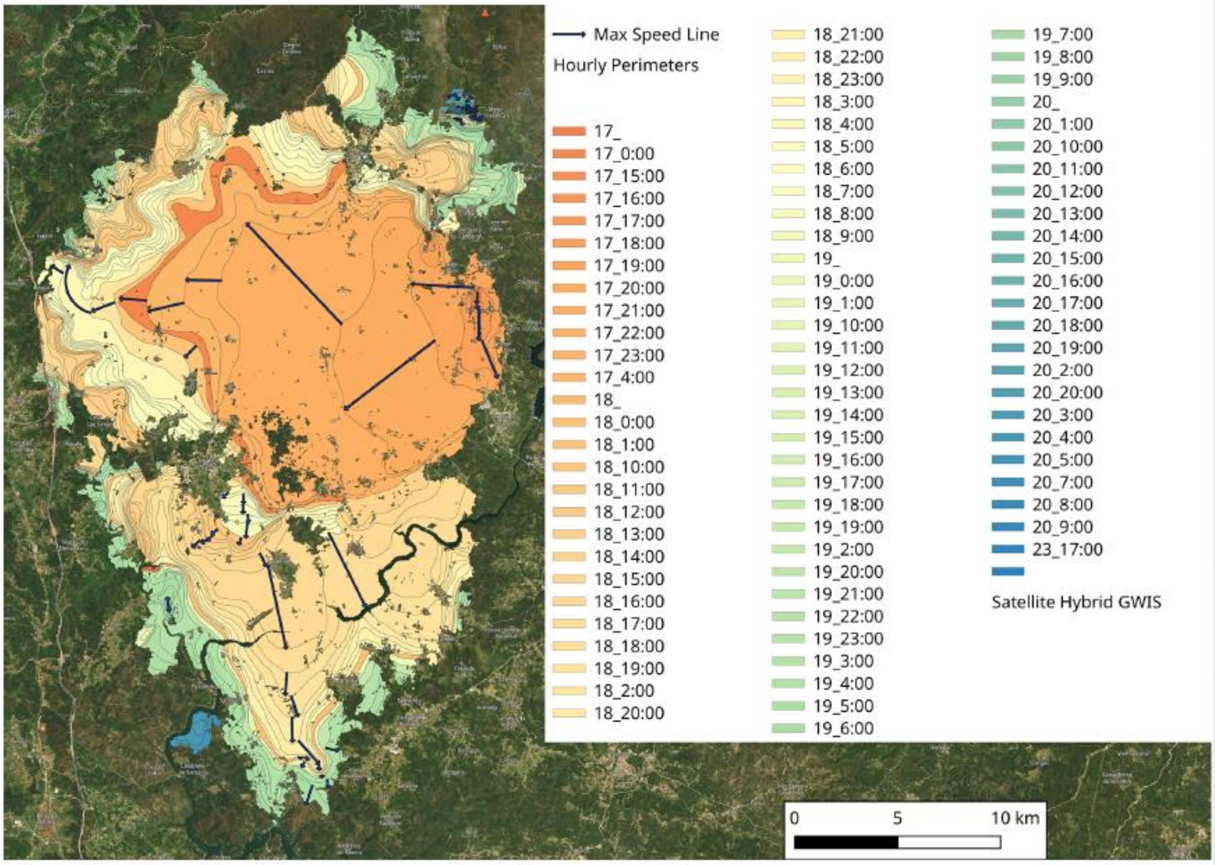

Fig. 8. Time sequence of the wildfire which took place in Pedrógão Grande (Guerreiro, 2017), Portugal on 17th of June of 2017. The maximum speed line between time steps is shown with a black arrow. Background image © Map Tiler *(https://maptiler.com/copyright)* [Fig.6, Artés et al., 2022].

- **There might not be a unique factor that is accountable for the definition of extremeness** (Fig. 9, Fig. 10). A fire is a very complex phenomenon, and measures of deep convection and stability conditions, such as with EFBI index, appear to show some results, albeit these measures need to be improved.

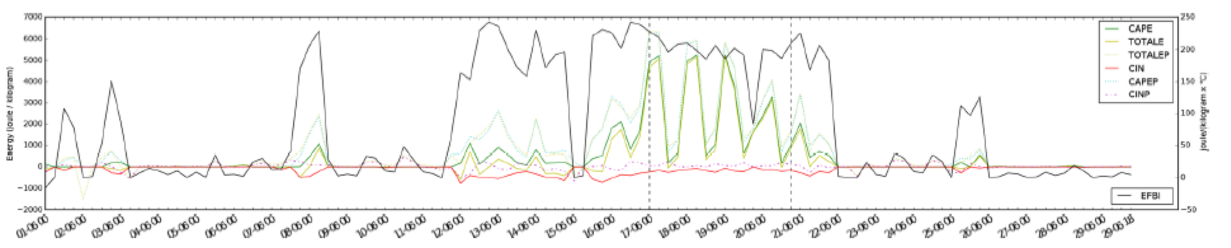

Fig. 9. EFBI and its components for the wildfire in Pedrógão Grande in June 2017 for the fire centroid (-8.2252, 39.952). Horizontal axis is the timeline using hourly steps in the format dd-mm hh. Vertical axis is the Energy, on the left using Joule/kilogram and on the right is Joule(kilogram·°C) [Fig.7, Artés et al., 2022].

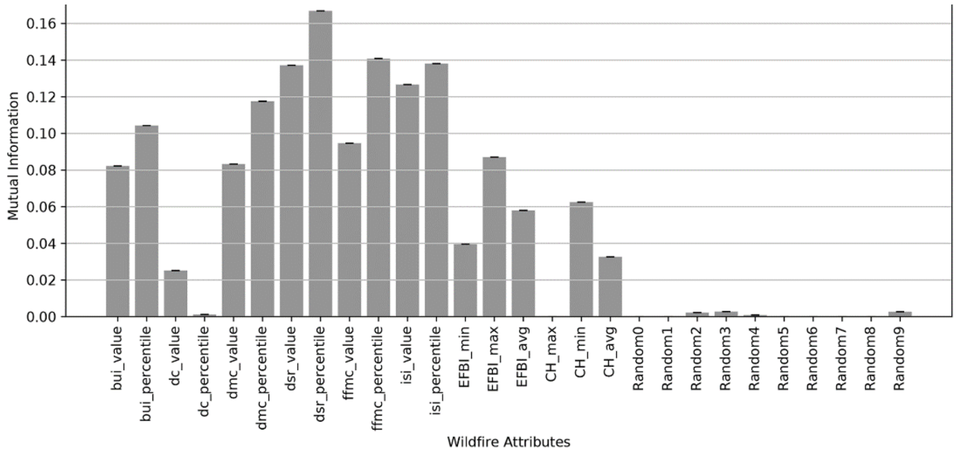

Fig. 10. Mutual information (MI)[2] of the different attributes gathered for each fire regarding their tag as fast or slow fires. CH: cHaines. Regarding the information of the different features used to discriminate small from large fires, this figure shows the values of the MI mean and standard deviations of each attribute for the 1000 iterations. The use of only the minimum, maximum, or average of the EFBI provided more information to separate small from large fires than the percentile and value of the drought code (DC) of the FWI. The figure 2022] (cHaines: continuous Haines Index).

- **Global monitoring systems cannot function in isolation, they must work with local entities and specialists in the area where EWE occurs, because the knowledge is there.** Global information can be useful, but detailed information and high-resolution perimeters are required to discern some trends and linkages. Simple metrics of atmospheric stability could provide valuable information for enhanced fire danger rating applied at global scale [Artés et al., 2022]. In Pedrógão Grande it was necessary to have EFBI values higher than at least 200 J/kg/°C to reach speeds higher than 2-3 km/h (Fig. 11). However, in order to collect this type of information, it is essential to have data from local entities since the level of detail required is significant (Fig. 9, Fig. 11, Fig. 12). Furthermore, some of these phenomena can change significantly throughout the day (Fig. 12). As a result, when indices are utilized at the global level, some aspects are blurred, and it might be difficult to detect linkages and patterns. In Fig. 13, for example, the lines for the maximum longitude of the daily burned area and the EFBI index and its components could be compared but there does not appear to be an evident relation, despite the appearance of some peaks where both elements coincide. It can be also seen that when there is some peak on the index, there is also another peak with some delay that marks a change on the fire, although the relation is not strong enough to indicate a correlation.

  There are case examples of this type of joint work:

[2] The MI of two random variables is a measure of the mutual dependence between the two variables.

- Roboré, Bolivia, Sept.-Oct. 2019 Extreme fire behaviour forecast analysis for EU Civil Protection, DG-ECHO, and EEAS.
- *Análisis de Incendios por Convección en Bolivia 2019*. JRC Technical Reports.

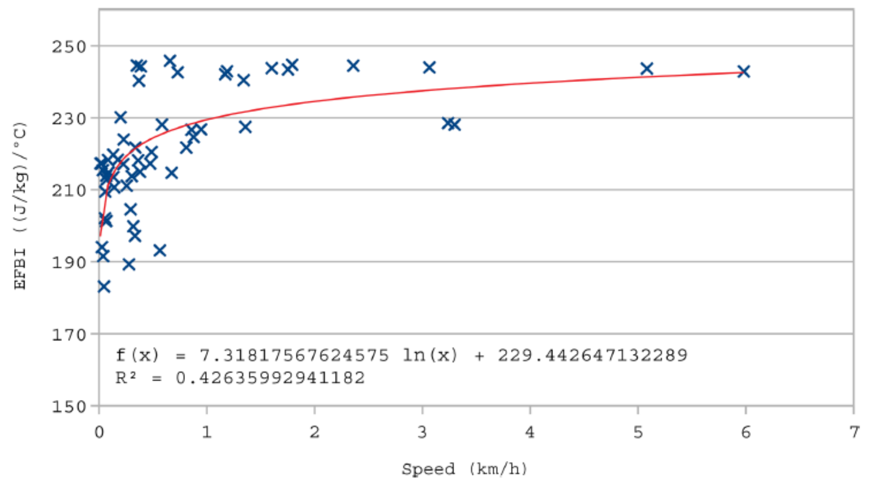

Fig. 11. Scatter plot showing the maximum fire front speed and the values of the EFBI for each time step with a logarithmic trend line. [Fig.8, Artés et al, 2022].

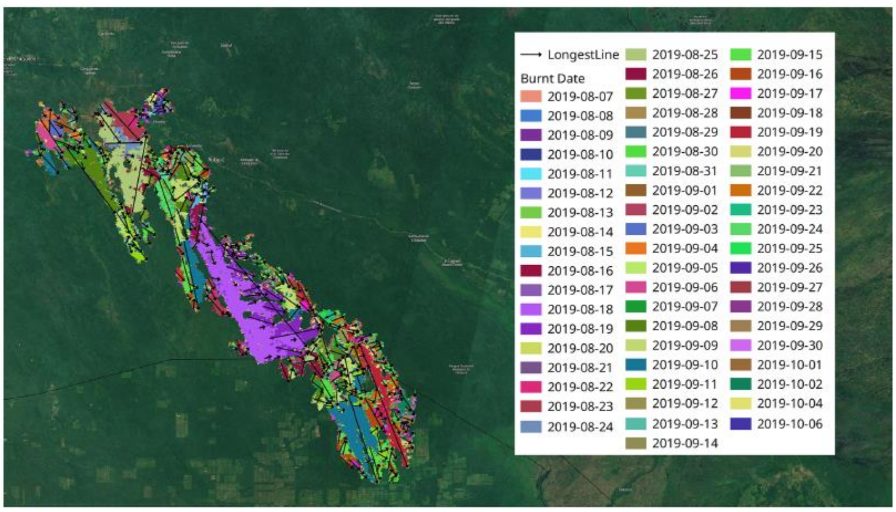

Fig. 12. Daily burnt area for the duration of wildfire in Roboré, Bolivia, in 2019. The maximum speed line between time steps is shown with a black arrow. The missing days do not have any daily burnt area in GlobFires. Background image © MapTiler (https://maptiler.com/copyright,last access: 18 March 2021). Please note that the date format in this figure is yyyy-mm-dd [Fig.9, Artés et al, 2022].

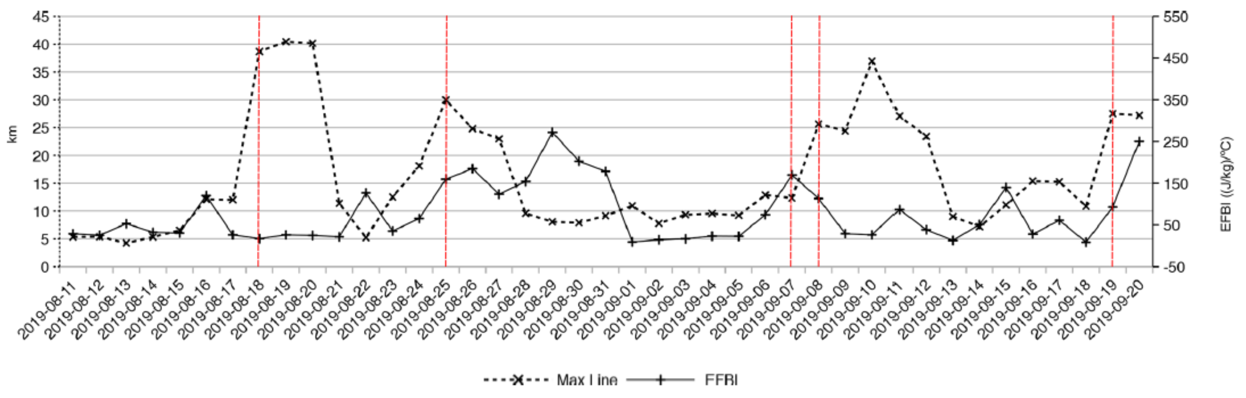

Fig. 13. Maximum longitude of the daily burnt area and the EFBI and its components for the wildfire in Roboré, Bolivia, in 2019. Vertical dashed red lines show when a PyroCb took place. Please note that the date format in this figure is yyyy-mm-dd. This figure shows the computation of the daily EFBI average joining the data from the different forecasts. In addition, the GlobFire database was retrieved and used to estimate the maximum daily fire run. Since the daily burnt area could have been mapped with some days of delay, an average was applied to the maximum daily fire run using a time window of the 2 previous days. The figure shows a peak of the EFBI followed by another one which started on August 16th and a third peak on August 22nd. After the first peak, the maximum fire longitude of the daily burnt areas increased from 16 to 20 of August, while the highest runs of the fire happened between 18 and 20 of August; the fire activity has another peak after 22nd of August, having two observed PyroCb clouds on 18 and 25 of August. After 25th of August, the EFBI trends seem to be totally uncorrelated with the fire runs until 1st of September. Afterwards, there is another peak on 7th of September which also seems to affect the fire runs, with two observed PyroCb clouds on 7 and 8 of September. Later, the EFBI and the maximum line length are again uncorrelated until 17th of September when there is again a relation at the last peak of the run, when another PyroCb was observed. [Fig. 10, Artés et al., 2022] (PyroCb: Pyrocumulus)

List of lessons learned highlighted about the European context

- The categories “fast” and “slow” do not imply whether or not a fire is extreme.
- Fire regimes and fire behaviour are changing, according to the EFFIS/GWIS database.
- Wildfire seasons are becoming longer and with a trend to be more intense.
- If only taking information from the news, one can observe that some fires that might be common in some places are unusual and bring a lot of attention in other countries.
- The EFFIS/GWIS database attempts to search everywhere using the same methodology, but it does not see everything (small fires, understory fires, prescribed/wildfire, and so on).
- Local data is frequently more accurate but it is also less available or comparable.
- Data and experience sharing leads to increased knowledge.
- We can try to define thresholds determining which fires are exceptional or considered extreme for a given place using historical data.
- We might also define absolute thresholds based on fire behaviour using the same criteria everywhere.

- However, risk is related to means and firefighting capabilities, factors which vary depending on location and time.
- Data from Earth Observation or computing capabilities cannot check (detect, track, etc.) everything. Simultaneous fires are a stress element, and we observe fires that are larger than a given threshold.

- Fire spread models hardly represent reality because they use methods that do not incorporate actual parameters or predictions of EWE. The key factor is to consider the key parameters that generate EWE in the models. Data assimilation and calibration methods need to be adjusted also to EWE.

Extreme Wildfire Event

The concept

What is an extreme wildfire event?

This section is based on the presentation ***Extreme Wildfire Events (EWE): real cases*** that took place during WS1 by Mr. Marc Castellnou (CFRS). The definition is also based on the elements addressed throughout WS1 that refer to the concept, as well as the outcomes of the specific session 'EWE concept definition' which took place during WS1 dedicated to this aim with the participation of Andrea Duane (CTFC), Elena Górriz-Mifsud (CTFC), Marta Miralles (CFRS), Miguel Mendes (TSYLVA), Míriam Piqué (CTFC), Teresa Valor (CTFC), and Xavier Joseph (TIEMS), and it included a time for discussion and debate with WS1 attendees. The annex contains further information and specifics on the definition process as well as all of the elements that arose as a result of it.

Extreme Wildfire Events (EWE) are defined as wildfires with large-scale complex interactions between fire and atmosphere generating pyroconvective behaviour, coupling processes, that results in fast, intense, uncertain, and fast-paced changing fire behaviour.

- It results in fire behaviour exceeding the technical limits of control (fireline intensity 10.000 kW/m; rate of spread >50 m/min; spotting distance >1 km and exhibiting prolific to massive spotting based on Tedim et al. 2018 [Fig. 14], and extreme growth of rate (surface per hour, ha/h) values).
- At the same time, given current operational models, this extreme fire behaviour is unpredictable, with observed fire behaviour well surpassing the expected. This overwhelms the decision-making capabilities from the emergency system (firefighter crews and emergency managers, infrastructure managers and civilian population).

It may represent a heightened threat to crews, population, assets, and natural values, as well as have relevant negative socioeconomic and environmental impacts.

	Fire Category	Real Time Measurable Behavior Parameters			Real Time Observable Manifestations of EFB				Type of Fire and Capacity of Control *
		FLI* (kWm^{-1})	ROS (m/min)	FL (m)	PyroCb	Downdrafts	Spotting Activity	Spotting Distance (m)	
Normal Fires	1	<500	<5 [a] <15 [b]	<1.5	Absent	Absent	Absent	0	Surface fire Fairly easy
Normal Fires	2	500–2000	<15 [a] <30 [b]	<2.5	Absent	Absent	Low	<100	Surface fire Moderately difficult
Normal Fires	3	2000–4000	<20 [c] <50 [d]	2.5–3.5	Absent	Absent	High	≥100	Surface fire, torching possible Very difficult
Normal Fires	4	4000–10,000	<50 [c] <100 [d]	3.5–10	Unlikely	In some localized cases	Prolific	500–1000	Surface fire, crowning likely depending on vegetation type and stand structure Extremely difficult
Extreme Wildfire Events	5	10,000–30,000	<150 [c] <250 [d]	10–50	Possible	Present	Prolific	>1000	Crown fire, either wind- or plume-driven Spotting plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Chaotic and unpredictable fire spread Virtually impossible
Extreme Wildfire Events	6	30,000–100,000	<300	50–100	Probable	Present	Massive Spotting	>2000	Plume-driven, highly turbulent fire Chaotic and unpredictable fire spread Spotting, including long distance, plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Impossible
Extreme Wildfire Events	7	>100,000 (possible)	>300 (possible)	>100 (possible)	Present	Present	Massive Spotting	>5000	Plume-driven, highly turbulent fire Area-wide ignition and firestorm development non-organized flame fronts because of extreme turbulence/vorticity and massive spotting Impossible

Note: [a] Forest and shrubland; [b] grassland; [c] forest; [d] shrubland and grassland; *FLI classes 1–4 follow the classification by Alexander and Lanoville

Fig. 14. Wildfire events classification based on fire behaviour and capacity of control [Tedim et al., 2018]. (FLI: fireline intensity; ROS: rate of spread, FL: flame length; EFB: Extreme-fire behaviour index; PyroCb: pyrocummulus).

EWE and big wildfire emergencies are not the same thing. An EWE can turn into a disaster if it directly affects and exceeds the coping and resource capacity of the emergency system and communities (Tedim et al., 2018). Big wildfire emergencies can be devastating, burn a large area of land, cause a lot of damage, or have lethal effects for people (including human fatalities). The process that leads to major emergencies may be known and expected, yet it may still transcend the technological capabilities of management. But on the contrary, **extreme wildfire events cannot be predicted**.

In July of 2018, Sweden had its worst season in history. Europe was involved in assisting the country, which had experienced various fires during the period in areas such as Värmland, southeast of Kristinehamn, and Edsvalla. The fire was intense, but not extreme. However, the event was considered 'extreme' since Sweden was overwhelmed and required external help due to a big wildfire emergency. The fire behaviour was uncontrollable, but it was not a pyroconvective unpredictable behaviour.

During the same month, more than 90 people died and over a hundred more were injured due to wildfires in a coastal area of Attica in Greece. Nonetheless, based on the burned area (ha), it was classified as a small fire.

The term "extreme" refers to those situations that surprise the system and cannot be predicted. If they cannot be anticipated, the assessment, tactical decisions and decision-making will probably fail, and this may entail legal consequences.

In regard to the point indicated above in the definition (pyroconvective due to large-scale complex interactions between fire and atmosphere), the most advanced existing method of predicting pyroconvection today is the Pyrocumulonimbus Firepower Threshold [PFT, Tory and Kept, 2021]. This index allows the identification of atmospheric conditions that favor deep, moist plume growth in wildfire smoke plumes, which estimates a theoretical minimum heat flux (or firepower) required for plume growth, [Tory, 2020]. Fig. 15 is the application of PFT to the Pedrógão Grande Fire (Portugal) wildfires in 2017 and it is currently the most advanced existing way of predicting extreme fires:

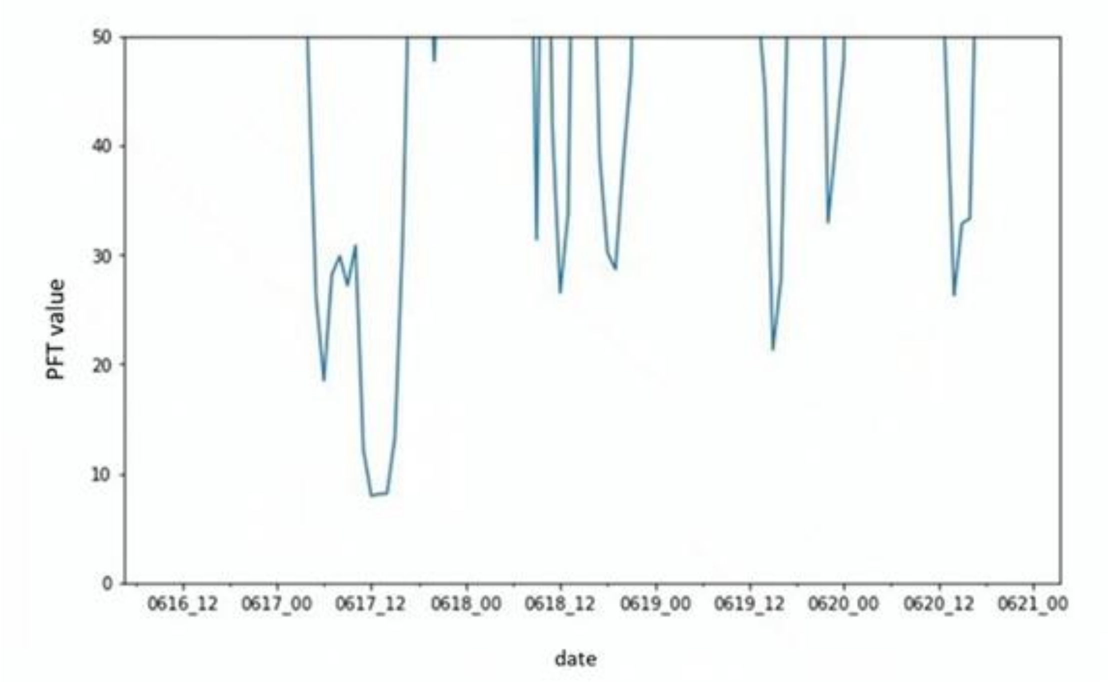

Fig. 15. PFT for Pedrógão Grande Fire (Portugal) wildfires in 2017. Graphic showed by Marc Castellnou during his presentation at WS1.

In 2017, using this type of index was not viable due to a lack of knowledge about the PFT. In 2021, the index started to be implemented after the events of 2019 in Australia [Tory, 2020].

On-field observations indicate that, the PFT index value must be below 5 to have a PyroCb. Thus, in Fig. 15 shows a good value for pyroconvection on the 17th of June at noon (X: 0617_12) (around 8). With this value, we would currently consider the possibility of a PyroCb forming at noon. However, the 2017 severe event occurred at night-evening and was one of the strongest ever observed in Europe. Therefore, **even with the best current knowledge, the Pedrógo Grande Fire could not have been foreseen.**

Today there are supercomputers applying advanced physical models (ex. MicroHH; https://microhh.github.io/) ready to simulate some parameters. **But it takes 6 hours of a supercomputer to run a simulation of half an hour**, making it unsuitable for on-field operations.

Currently, fires can be classified in terms of intensity, rate of spread, flame length, spotting activity [Tedim et al., 2018] and, in case they show pyroconvection, they can be classified in terms of *indraft* and *downdraft* (according to on-field observations).

Unfortunately, this information is insufficient to comprehend the phenomenon because **the microphysics involved in the fire-atmosphere coupling of these EWEs is not yet well understood**.

During the 2020-2021 period, Argentina suffered huge fires involving simultaneity and high intensity behaviours. The fires were located in the Costa del Tornero complex and in Boquete, in El Bolsón, in the Río Negro province in January; and in Chubut, the province to the south of Río Negro, in Las Golondrinas in March.

Throughout these massive and simultaneous events, it is highly probable and expected that the emergency response, the society, etc. will be overwhelmed because it is difficult to detect them from the historical data or indexes based on them; and in some cases, it may even be assumed that nothing can be done to stop the fires, at least in some specific locations. **But there are also cases of small fires, that suddenly overwhelm the emergency response, society, etc. as well**.

Extreme Wildfire Events are not a new phenomenon, nor is the concept of fire weather, but data from these phenomena is not yet included in current models for monitoring, prediction or training.

For example, in Catalonia, the fire service witnessed extreme wildfire outbreaks in the 1980s, 1990s, and early 2000s. The distinction between previous EWE and contemporary EWE is that in the past, they needed to be huge to show unpredictable extreme behaviour, whereas such behaviour is now displayed even with a smaller dimension.

In 2021's fire season, different small fires (5 ha, 10 ha, 20 ha) already showed unpredictable fire behaviour. The situation seems to be linked to the level of heating in the atmosphere, which corresponds to the level of instability in the boundary layer. However, this type of data is not yet employed in prediction or training models.

The concept of fire environment is not new either. The concept of fire weather comes from 1972 but it is still unpredictable because fire spread models do not work properly under fire weather conditions, and thus the assessments and decisions based on them can be wrong [Countryman, 1972].

The changes in weather, climatic and socioecological mechanisms are changing the regime of extreme wildfire events.

On the one hand, all of the recent efforts, knowledge, and science have contributed to a reduction in the number of burned hectares and fires per year in various southern European countries. On the other hand, from the operational perspective, it has been seen that the number of days when the fire risk is extreme has increased, resulting in fire seasons that are stronger and longer than they used to be.

There are many types of fire behaviour and distinct fire behaviour regimes. They may differ due to different types of weather and diverse vegetation fuel, but responders have observed a rise in a new form of fire regime that has not previously been documented. **One of them is linked to the high-pressure systems blocking the Atlantic flow over Europe** [Duane, Castellnou & Brotons, 2021]. **That blocking used to happen once every 3 years, and now happens at least 5 times per year in average. This is changing the regime of extreme wildfire events.**

The fire regimes are changing due to unstable atmospheres, novel climates (new interactions between drought, hot environments and novel wind situations (e.g., hurricanes) and new fuel availability (more vapour pressure deficit increasing vegetation stress, shifts in aridity pushing weather-limited fire regions to increased fire activity, the lengthen of fire season increasing vegetation stress) [Duane, Castellnou & Brotons, 2021].

The response system has learned to manage convective fires by understanding their behaviour and containing them. However, previously known and typically operationally affordable wind-driven flames have suddenly become convective wind-driven fires, overloading the system once more.

Climate change is bringing extreme weather. But even in the worst weather conditions, also the availability of fuel in the landscapes makes a difference. The amount of energy stored in the landscape that can be released in a single event is one of the key factors on the development of EWE.

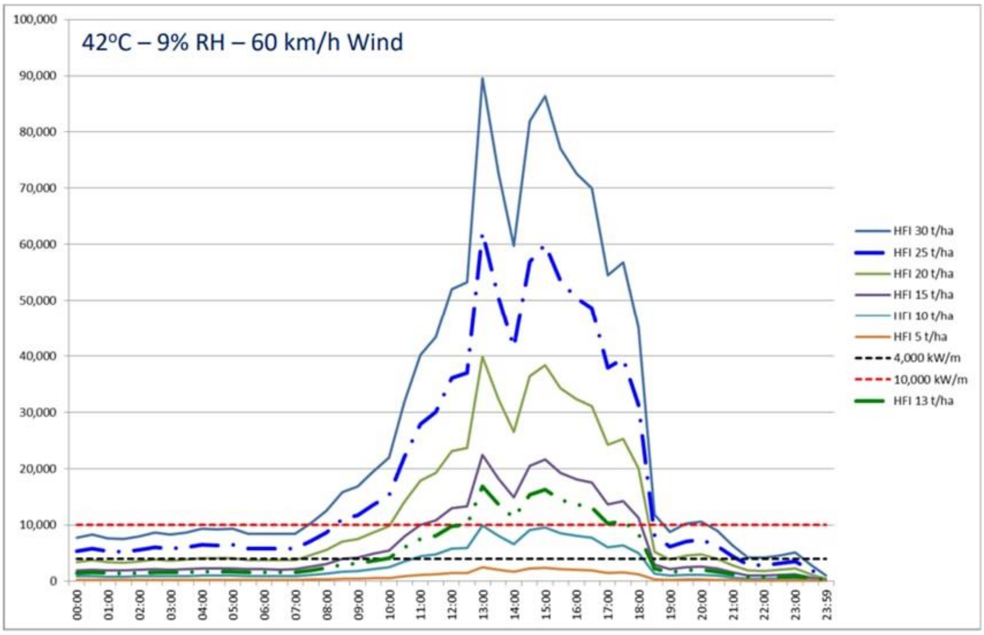

Fig. 16. Diurnal Head Fire Intensity HFI (Kilmore Gap Weather Station, 7 February 2009) simulated under different amounts of fuel loads in the landscape. The dashed lines indicate the limit of radiation that fire suppression can withstand (in red) and the threshold above

which firefighters will get burns in their skin, even having the protection equipment (in black). Source: Marc Castellnou and Al Beaver.

Fig. 16 shows the worst conditions in the Black Saturday fire in 2009 and the fire line intensity (vertical axis) that can exist depending on the fuel load in the landscape. Values around 9.000 kW/m energy are considered excessive and above 10.000 kW/m firefighters will get burn, even having the protection equipment (clothes, etc.). So, it is not possible to extinguish such intensities by human means.

As already mentioned above, extreme fires are those that cannot be predicted. There are also fires that can be predicted, exceed 10.000 kW/m, and can overwhelm the system. But in this case, we would be talking about large fires but not extreme wildfire events, because they do not have the component of unpredictability.

The energy stored in our landscape that can be released in a single event seems to be a key factor for the development of EWE.

Climate change is bringing extreme weather to the situation, but according to Fig. 16, even in the worst weather conditions in Australia, only forests with less than 10 ton/ha of fuel load in the landscape available would not have caused a potential extreme fire behaviour. So, it seems that one of the key factors that can be directly associated with the concept of an EWE is the energy stored in our landscape that can be released in a single event.

Recent global events indicate to the emergence of novel extreme wildfire events not reported previously and associated, in many areas, with higher frequency of events than expected [Duane, Castellnou & Brotons, 2021].

It is important to make an effort to comprehend how this large-scale phenomenon of EWE operates, as the consequences and impacts go beyond the fire's own perimeter and environment and at the moment remain unpredictable and uncertain.

Because the 2017 fires in Portugal were identified as EWE and happened in Europe, they should be at the forefront and within the scope of this project. They occurred after Las Máquinas wildfire in Chile (2017) and it was the first time that it was seen a fire burning at 8.000 ha/hour speed at night. However, at that time, it was considered an exceptional and extremely rare case. This was the first time that records were kept. Probably in the past there were wildfires with this behaviour and they were not analysed. Similar incidents have occurred since then in:

- 2017 Portugal (June and October), Chile (January) and USA (October).
- 2018 Northern Europe (July), South Africa (October) and USA (July).
- 2019 Bolivia (August)
- 2020 Australia (September), Argentina (February-August) and USA (August-September).

So, since these kinds of events are no longer uncommon, it is worthwhile to investigate the existing cases, particularly the most significant one in Europe thus far: Portugal 2017.

In 2017, Ofelia Storm arrived in Europe after transitioning from a hurricane to an extratropical cyclone. The tropical storm was forecast to arrive in Portugal at noon, with sustained winds of approximately 67km/h. Given that there was an active fire at the time, it was predicted to rapidly expand and become large.

Figure 17 shows two graphics. The upper graph displays the evolution of wind speed in red and relative humidity (HR) in blue. The graphic at the bottom of the figure reveals the wind velocity from all of the weather stations near the fire in Portugal, as well as some from Spain.

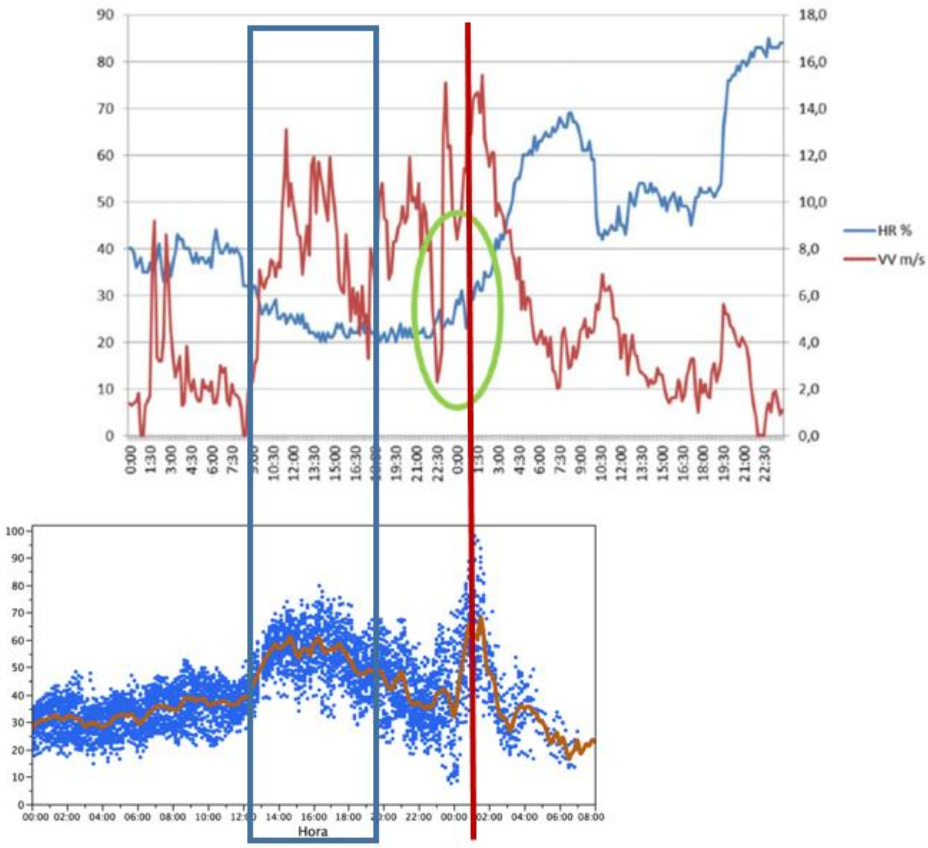

Fig. 17. Upper graphic: Maximum wind speed and relative humidity (10-minute intervals) at the meteorological station of Nelas (IPMA), during the 15th and 16th of October 2017. The ellipse marks the coincidence between the minimum wind speed, which precedes the maximum values, and the beginning of the rise in air humidity. Lower graphic: Wind speed (10-minute averages) at turbine level at Fajão wind farm, Pampilhosa da Serra, during October 15 and until 8:00 am on October 16, 2017. The line results from a cubic spline fitted to the set of individual observations. See the reduction preceding the maximum values recorded during the period. [Source: Fig. 3.27 and 3.28 from Avaliação dos incêndios

ocorridos entre 14 e 16 de outubro de 2017 em Portugal continental – Relatório final, edited by the Assembleia da República of Portugal].

The blue square in Fig. 17 shows a period of high winds (red line) and low humidity (blue line) but it can be seen that at some point (between 16:30h and 19:00h) the wind falls in all the stations in Portugal and Spain surrounding that fire. That was an expected situation, predictable, but leading to a huge fire with more than 1.000 ha burned.

Then the Ofelia Storm moved away but low humidity and high winds persisted (between 19:00h and 22:30h). That was nevertheless not unexpected because plumes are known to produce effects such as winds, *indrafts*, *outflows*, *downdrafts*, so this data could be due to these movements. Maybe it is not on the range of predictability by a model, but it is predictable when on-field observations, expertise, and other factors are considered. It falls under the category of "*we know we don't know*" yet still applies.

But then, the wind abruptly dropped (green circle in the graphic) without any connection to a frontal system in the area, and after that the highest wind-peak of the time appeared (red line in Fig. 17). All weather stations, not only those inside the fire weather environment stations, detected the wind. This can be seen observing that the data just in the middle between the blue square and the red line decreased in terms of wind, whether they were 1 km away of the fire or 100 km away from the fire.

This situation happened at the same moment when relative humidity began to rise (see the blue line in the graphic), in a typical case of moist convection downdraft. It was a high plume located 40 km above the fire that started to get humidity into the *indraft*. And that humidity was transported by the updraft up to the free troposphere. Once there it froze to -50ºC, causing precipitation, which resulted in a massive downdraft that could be felt hundreds of kilometres distant.

The size of the coupling effects between fire and atmosphere CAN be around 100-1000km.

The same situation was observed in Chile in January (2017). The night of the 25-26th of January.

The downdraft of the Las Máquinas fire was observed on the night of January 25-26, from a weather station 1000 kilometres into the Pacific Ocean (Juan Fernandez Island). **This suggests that the extent of the discovered coupling effects between fire and atmosphere could be in the range of 100-1000km.**

Non-extreme wildfire events solutions

This project focuses on EWE so innovations should specifically address this phenomenon. However, looking at the solutions provided for non-extreme circumstances can help to comprehend the underlying structure. As a result, some issues were raised during the workshop 1 discussions. It was specifically questioned what kind of actions are taken in organizations to deal with fires that do not have extreme characteristics, and the following points were highlighted:

1. **Prevention** managing the forests using prescribed burning, cutting down trees, making broad lines, selecting species of trees more prone to resilience. Prevention should focus on the mentioned solutions and not just on reducing ignitions. There will always be ignitions, so the key is to have opportunities to deal with wildfires and to have the landscape adapted to it, a landscape that avoids having the conditions that facilitate the occurrence of EWE.

   In Portugal the use of prescribed burning is traditional and therefore does not usually involve intense criticism. In contrast, in places like Chile, the use of prescribed burning is not allowed, and they are looking for mechanisms to introduce this technique in the forest management while in the fire operations they are introducing the tactical fire to increase their toolbox.

2. Another perspective offered from UK participant during the discussions was to focus on **mitigation**, on the basis that prevention is often complicated as there will always be ignitions. Under this perspective, it is proposed to address the impact of the fire, this is to consider what can be done once the ignition is already in place. Under this perspective, efforts would focus on prescribed fire training courses to land managers, forest managers and owners, training in safe prescribed fires, etc.

   There is a difference between a prescribed fire which is a controlled land management of the fire, and a tactical fire performed by firefighters. In UK, they have developed UK fire & rescue service for tactical burning. Some of those undertake fuel management as part of the training.

3. **Planning for uncertainty**. Planning is another option but doing this for EWE with a high degree of uncertainty is difficult. Forest management relying in the definition of forest fire potential polygons can open up opportunities. This may help to define places that will give some opportunities to firefighters to lead positive action on the fire. Even if it is an EWE maybe it will give some chance to make something at some place. So even under the uncertainty that these phenomena entail, it may be a good idea to manage the forest to look for these opportunities.

   Polygons of fire potential consist of dividing the landscape into pieces that allow the fire to be confined to this area, let it burn if necessary, during a wildfire event, avoiding the jump to another area. The methodology is used in other risks, such as fires in industrial buildings, where there is a sectorization. When there is a big building with different parts, and a section is burning, perhaps this part will be lost but not all the building.

4. Existing **emergency planning** should be updated to include the reality of EWE and climate change. Plans made 10 or 15 years ago have become outdated. The new plans of civil protections should go hand in hand with the reality of new emergencies due to the climate change.

Lessons learned

This section is based on the discussions and highlights on 'EWE PROCESS/BEHAVIOUR DRIVERS challenges and gaps' with participants Akli Benali (ISA), Brian Verhoeven (NIPV), Jordi Brull (CONAF), Jorge Saavedra (CONAF), Marc Castellnou (CFRS), Marta Miralles (CFRS), and Miguel Angel Botella (VAERSA).

Portugal 2017

Fire behaviour in Portugal has evolved over the last decades (years) due to the increased frequency of PyroCb and the related intense fire behaviour. The circumstances that occurred in the Pedrógo Grande Fire in 2017 could not have been predicted. Even today, many of the details of what happened are still unknown. Therefore, it remains difficult to predict this kind of events. For example, the conditions on the second and third day seemed more favourable than on the first day, but in reality, the situation was worse those days [See previous section for further information about the event], and the existing indexes do not allow to predict that this would happen in the evening with the increase in relative humidity and drop in temperature.

As larger-scale fire-atmosphere interaction becomes increasingly common, fire behaviour is altering. The development of this event cannot be predicted although there is a strong investment from the emergency managers on fire suppression resources to success on these situations. Large investments across EU have been done and they have resulted in low impact on suppression efficacy and efficiency.

It is crucial to successfully connect research to the needs of practitioners. To produce a solution, a beneficial impact, and an appropriate partnership between researchers and practitioners, it is necessary to bring together research and responders (Fig. 18). However, before experimenting with new techniques or technologies, the responders' true problems must be identified. This is accomplished by asking questions, conversing, dialoguing, and comprehending the field work and the issues they face. Responders must raise questions, observations, and difficulties, while researchers can offer methods.

	Doesn't know he has a problem	Knows he has a problem, doesn't know the solution	Knows he has a problem, knows the solution
Doesn't want to know the practical problem	Business as usual		
Doesn't know the practical problem		Knowledge transfer	
Knows or wants to know the practical problem			Co-creation

Fig. 18. Researchers' vs Practitioners. Source: content from Akli Benali presentation during WS1.

It is important to work on reinforcing the decision-making system and understanding the fire behaviour to see where to focus responders' efforts.

Following the 2017 fires in Portugal, several indicators were developed to improve the tactics. Some examples of the developed tools are: a periodic weather report so that firefighters know the situation and are able to interpret it, an application (APP) to collect data on the fire by firefighters to transform it into GIS information, tools to quickly predict the expected behaviour of the fire and the weather conditions or a database to collect information about how fires have burned, what burned, when and how it did it, to be useful for later analysis. Fig. 19 shows more examples.

Decision support tools	Fire analysis products	Operational dynamics
• Fire management platform for the entire country (**FEB Monitorização**) • **Prescribed Burn platform** • Contribution to the web platform of pyro-meteorology (**Multisites**) • **Public tutorials** (videos) on decision support tools (https://www.youtube.com/c/FEPCGAUF) • Contribution to the development of a **fire simulator (research)** • **Fire energy monitoring application**	• **Strategic Operational Analysis** • Types of **meteorological products** in articulation with the IPMA • **Operational Information Model** for the Commander incident • **Daily presentation at the National Relief Operations Command** regarding the wildfires of the last few days and the fire potential for the next few days • Co-creation with of **risk maps (research)**	• **Researcher working in the analysis cell** • Use of surveillance cameras for decision support • **Monitoring aircrafts** • **Operational instructions** for all agents (case studies, use of operational tools, fire analysis, etc) • **Prescribed Burn** with firefighters • **Operational exercises** • **Exchange of experiences** during wildfires with other international teams

Fig. 19. Developments from practitioners after 2017 fires in Portugal. Source: Akli Benali presentation during WS1.

These parameters help to differentiate extreme behaviours by looking at the range of values. When drawing a graph with the two values, it depicts and helps to differentiate growth patterns of the head of the fire versus the flanks of the fire. They are key values necessary for decision making.

Needs and opportunities

Some of the needs and opportunities detected from Portugal were listed during WS1. The following is the list as it was provided in order to see some of the significant points raised:

1. Simplify and 'keep it as simple, stupid' (KISS)!
2. Integrate simulation tools with pre-suppression!
3. Develop indicators based on convective behaviour!
4. Prioritize emerging wildfires!
5. Automatic wildfire perimeters availability!
6. Integrate fire spread simulations in WebGIS!
7. The use of radiosondes in wildfires
8. Perform pyrocumulus analysis (e.g. satellite, radar)!
9. Have better information to support better decisions!
10. Have interoperable solutions!

These points were determined for Portugal, but they may serve as an illustration of the kind of elements detected.

Key variables to identify and predict scenarios

Today it is still not possible to explain in detail what happened in Portugal. Considering the impacts of the 2017 fires, it is vital to address the lingering questions before moving a step forward. The models do not integrate the changes in the variables caused by the interaction of the fire with the environment. Even though there is a lot of information (indexes, parameters, etc.) compared with the past, we are still unable to predict where, when and for what reason these EWE occur.

During a fire, soundings can be used to compare the profile inside and outside the fire. Catalan Fire and Rescue Service has already done this in some cases, and it has been observed, that the increased ambient humidity has a role as a trigger towards the more extreme fire behaviour moments. This may be related to the effect of fire on the ambient humidity, which is a complicated value to measure. Atmospheric humidity and how it influences the EWE is a field on which to focus efforts.

Some fires have recently been observed at night (ex. in Chile, 2017), totally beyond the capacity of suppression. There are now clues regarding how these fires work, but simulators have not been able to represent them, therefore they diverge from reality and on-field scenarios. Although responders generally expect fires to be at their most intense during the day, many fires have occurred throughout the world at night. At the moment, the movement of the layers of the atmosphere may be explained, but not the EWE phenomena.

The capacity to anticipate EWE

Models

In Santa Coloma de Queralt fire (2021, Catalonia) responders knew they could have a Pyrocumulonimbus (PyroCbN), **but they did not know when it could appear**. This information would have been crucial in defining the strategy and tactics to decide whether to keep crews inside the perimeter when the PyroCbN began, or to evacuate them for safety reasons so that they could return to work thereafter. It would have been important to know the period when to be out of the perimeter and when to come back again, and to be able to explain the situation to the crew as fast as possible.

Wildfire simulation tools are utilized in a variety of settings and purposes. Some are based on one module as BEHAVE, with Rothermel's model, and others use different simulation modules as FARSITE, that implement crown fire and spotting fire modules. However, new generation tools, like WFA, provides good simulation performance on current EWE using real-time adjustment supplied from the field to set up the final simulation environment.

Additionally, high-definition wind fields and various simulation modules to improve performance during crown and spotting fire events complement the simulation platform. The problem remains in proper physics in the model to correctly predict the fire spread processes rather than anticipating the fire perimeter position at a certain time.

Nevertheless, the models showed limitations in current EWE situations where simulation tools were in place, as Las Máquinas (Chile), Pedrógão Grande (Portugal), Jubrique (Spain), or Rio Llano (US) fires. On those cases, adjustments to real-time spread, fuel types, and wind fields were needed to adjust the fire spread position to be similar to the one shown in reality. This was done during the review process. Those review processes using existing simulation tools are providing the best clues to improve simulation modules where Artificial Intelligence (AI) can be implemented to perform better in real-time. Recent experimental simulations during PyroCu/Cb-driven fires in Spain and California paved the way for AI coupled model implementation. The Pedrógão Grande fire has been recently simulated with Jean-Baptiste Filippi et al. 2009 (CNR) coupled fire Simulator. It still doesn't allow real-time prediction to be used on the field.

Although limited, tools went a long way after 90's applications such as BEHAVE, FARSITE or PROMETHEO. Today's devices are getting close to implementing coupled modules to simulate fire-atmosphere effects on fire spread. **Research on coupled physics as well as focus on fire spread processes (improve good fire perimeter position forecast already provided with today's tools) are the hot topics for improving simulation capabilities and confronting EWE in the near future**.

High quality information is required, but at the same time there is a need for operational solutions because the results need to be ready in a short time (ex. 30 minutes) and in orders of magnitude of hundreds of metres. Despite the commented on previous paragraphs of this section, they have been showed to be useful for other purposes as e.g., evacuating a village (Fig. 20) and although the result is not exact it can work for that purpose in some situations.

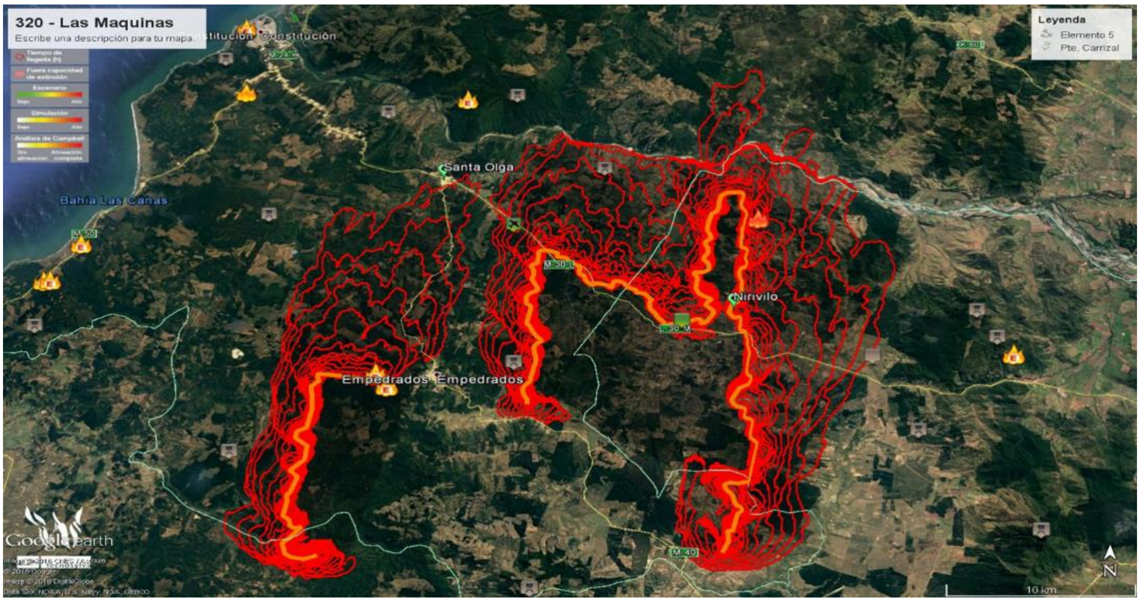

Fig. 20. 12-hour simulation example with Wildfire Analyst delivering spread trends to evacuate a village in Chile 2017.

Indexes

There are indexes that are not suitable for EWE. Ex. Haines' index[3] works well for the conditions for which it was designed, but not for pyro-convection.

Chile has indexes that reflect the reality of a vast portion of the territory, but do not work on a small scale. They seek to know where the ignition will be, and they have had to adapt some indexes to state-level (very large scale). But they are not yet at the level of showing how big the fire can become or how much energy the EWE will have. At night these indexes are not useful.

The capacity to collect real time data both at an appropriate scale and also vertically in the atmosphere

Knowledge has been built on the basis of what is known and unknown but a more adaptive way of proceeding could be considered based on observations and patterns.

Identification of the key variables and level of detail

A lot of time is spent on improving the models, but not enough on gathering real-world fire data, so it's essential to strike the right balance.

[3] Haines DA (1988) A lower atmospheric severity index for wildland fire. Natl Wea Digest 13(2):23–27.

In Catalonia, for example, predictions are based on patterns identified from fuel and weather conditions rather than models. As a result, in a common shared database, global patterns can be found which could be used to apply statistical correlation between data from different fires if required.

Available data

The capacity to collect real time data means that there is not much data available for all EWE. Even in those relatively small sites with quite a few observers, the problem of having available data also exists. For example, Catalonia territory is smaller than others in Europe, which favours having more people observing on-field, and although there is also certain amount of data, the problem is still unsolved.

Safety areas

When the conditions are extreme, in some cases staying indoors might have serious consequences, and people may be forced to evacuate. Therefore, it has to be seen how safe zones relate to such situations in the context of EWE.

Challenges

A number of issues remain unanswered, and efforts should be directed toward resolving them. The following list does not show the priority order but a list of elements that were highlighted during the discussion. Elements marked with an asterisk [*] are discussed in more detail in the following section.

1. To answer to the question **why Pedrógão Grande Fire (Portugal 2017) behaves differently one day compared with the next day and in one moment compared with the others**. It is important to approach the question because it was an event in Europe which is the geographical framework of this project and in order to define the drivers that underpin the event and learn for future events.
2. **The mathematical models (algorithms) of the simulators do not accurately describe reality**. They do not accurately forecast extreme fire behaviour, with statistical robustness and sensitivity. To make operational decisions, predictions on extreme fire moments, changes in fire direction and growth patterns in those moments among others should describe reality sufficiently well. We need to develop operational coupled atmospheric models to analyse processes and understand how fire interacts with the atmosphere, in order to make operational decisions.
3. **Operational solutions need to be ready in short periods of time**. Operational models need to focus on what is required in a short period of time and be prepared with readiness. Forecasts are often needed in less than 24 hours to be operationally useful.
4. **Simultaneous fire interaction**. When simultaneous fires exist, it is not clear how they interact and how a PyroCbN can be generated from them. It is important to put the focus of research and analysis on knowing about on the interaction between separate simultaneous fires.

5. Large spreads of fires at night are a challenge to be understood, predicted and incorporated into strategies and tactics. And they are a challenge because at night it is when conditions typically and theoretically are expected to improve. Also, reignitions seem to be a problem in different regions (Portugal, Catalonia, etc.). **Key variables to identify and predict risk scenarios in order to make operational decisions are essential. A better understanding is needed on growth patterns both feeding and resulting from pyroconvective events.** The linkage between fire and atmosphere is key, and the key variables need to be considered [*].
6. To have **the capacity to collect real time data both at an appropriate scale, and also vertically in the atmosphere** (perimeter of the fire, the energy available from the atmosphere and the changes that occur there, the temperature of the column, the probability of column collapse…) [*].
7. **To put the focus on predicting the moments of change**. There are moments when a lot of energy is released to the atmosphere and the driver for change is this moment of shift.
8. Organizations do not have the operational **capacity to anticipate extreme wildfire behaviour** with the current tools [*].
9. There is still not **accumulated experience** in these EWEs. It would be interesting to have a knowledge hub for wildfires and database cases based on unpredictability.
10. **The current protection measures for Wildland Urban Interface (WUI) do not work for EWE, so there is a concern about if it is legitimate to continue investing on such measures that do not address the problem of EWE**. In Chile, they have seen how the protection zones around municipalities have not worked in their territory. In Las Máquinas (Chile, 2017) the fire destroyed everything, even though the city had a safety perimeter, and people were evacuated. In Valparaiso fire the same situation happened, and the self-protection structure did not work either [*].
11. The more fuel you have, the greater the risk of exceeding the extinguishing capacity. If there is not enough fuel, it will not burn more than the extinction capacity. Therefore, **forests need to be managed to reduce fuel consumption and energy available and to guarantee that the fire suppression can be done in case of EWE**.
    From a landscape management perspective (WP2) it is important to focus on territorial management. From this field of expertise, the focus is not on the behaviour of the fires, but on what they have to do to manage these EWEs using the management of the territory that ends up having an impact on the spread of the fires. But to do this, the first step is **to understand the behaviour of the fire**, otherwise it will be difficult to have useful actions for prevention against EWE. If the behaviour of fire is unknown, it will be difficult to adapt the landscape management and plan real opportunities. So, it is important to solve the small problems approaching a large-scale scope to understand all the implications.
    From a **cost-benefit perspective**, it is also important to understand the behaviour of the fire and know what can be lost and what cannot, the impacts of the disturbance, etc. The landscape that we have today is the result of the decisions of the past, and

therefore today we are making the decisions that will determine what the forests of the future will be like (ecosystem response, carbon cycle, society…). Therefore, it is important to understand the behaviour of the forest and its variables (climatic range, structures…) in order to be able to adapt the management of the territory.

In the case of landscape, it would be interesting to undertake a **trade-off analysis** with numbers and studies about how the fire will **impact** the ecosystems (biodiversity; carbon; economy; society; hikers; soil degradation in terms of erosion, nutrients, and the cost of actions to prevent them; …).

12. **Social/economic/cultural disparities in land management** must be acknowledged, but no solution is currently available.
13. Focus on the **social aspects and the agents/stakeholders that form part of the landscape in order to understand what we are capable of doing as an emergency system and to prioritise**. By working on this, we will be able to take early decisions and manage not only the emergency but also the territory.
14. **Organic and moist matter indices** do not exist and would be useful.
15. To **quickly, reliably, and economically model the fuel and fuel moisture** using a feasible, viable and scalable approach (live fuel moisture content (LFMC); proxies from open data satellite images; climate modelling from ground network instruments …)
16. **It would be important to have more accurate atmospheric and plume profiling**. At the moment there are atmosphere profiles from simulations and models (e.g., skew-t) but not real profiles.

These challenges are not unique to one region, nor to the EU, but are shared globally. All countries need to adapt to local realities and to their own challenges. For this reason, it is also important to take advantage of global knowledge.

Guidelines

Key variables to identify and predict scenarios

It is important to focus on unexpected fire behaviours and notice when they occur, and then try to understand and forecast them. To recognize these abnormalities, it is necessary to understand the local fire kinds and problems, as well as the EWE. It's indeed essential to share global information in order to consider all available data and create a coordinated response.

Contrary to what might be expected, these EWEs appear with little wind and a lot of humidity. In past cases, simulators and responders did not expect this situation, it was counter-intuitive, and ended up having extreme behaviour. It is important to focus on what is unexpected and what cannot be explained at the moment, trying to understand and model it. So, it is important to gather real data (statistics) of different levels (height levels, types of data, etc.) during the fires.

It is also important to find how much energy it will be transferred from the fire to the kinematic of the fire plume (Clements & Charland, 2013). Not only the atmosphere is creating conditions for EWE, but also the surface processes, so the result is a coupling of these two.

The capacity to anticipate EWE

Models

Simulators are still not powerful enough to run coupled simulations involving real-time fire adjustments. For decision-making it is necessary to be able to adjust operative models as much as possible to reality. But in the actual models, the basic equations do not adequately consider the behaviour of the fire because they are based on the assumptions that do not correspond EWE behaviour (Finney et al., 2012). Then the physics of fire behaviour in the model does not correspond to reality, and this is mainly because the function of the EWE is still unknown. In his article (Finney et al., 2012), Finney proposes the anomalies between expected and predicted fire behaviour as the point to focus on. When studying these anomalies, it is important to understand the local fire types and challenges while considering that to understand the extremes it is important to share global information.

Indexes

In non-extreme wildfires, the indexes perform better than in EWE. There is currently no mechanism to detect when an EWE may occur, therefore it is hard to determine when to use or discard an index, hence the conclusion is that they are unreliable in these situations.

When we refer to the indexes, the scales at which they apply are a challenge if we are looking for a valid solution at all levels.

Large-scale indexes seem to perform worse than locally adapted indices. Some organizations work with adapted indexes (e.g., Portugal) and have been looking for indicators that respond better to extreme wildfire events. But even when these happen, there is a problem identifying it in advance, not only when the EWE has already happened. To be able to explain the phenomena after its occurrence does not imply that it can be predicted beforehand.

Radiosonde is currently the best way to explain what is happening. The method is based on the vertical profiles of the atmosphere, so real profiles are needed (radiosondes during the EWE that show energy and the possibility of convection).

So, the questions to be addressed are, whether we need to adapt the indices or create new ones, or whether there has any real predictive potential at all.

The capacity to gather real time data both at an appropriate scale, and also vertically in the atmosphere

Identify key variables and level of detail

Some models can be useful with some wildfires and situations, but they cannot predict all the necessary elements for EWE, and the ones that are best suited for that have the disadvantage of the time they take to do so (hours). It is important to identify the key variables and processes that lead to the development of EWE and integrate these aspects into the modelling, adapt the models accordingly and process the information in an optimal time for the operation of the response services. More and better information has been integrated in the models, but it is a matter of finding the relevant information to consider and adjusting or change them to be able to be used for EWE.

The land's humidity is measured using satellite images (pixels), and the output is a combination of soil moisture and vegetation moisture. According to the ICGC, it would be more interesting to incorporate the structure of the vegetation (by means of LIDAR, which is more real than using other type of data that incorporate approximations). It is important to set up the amount of detail required for the models to incorporate real-time data, such as soil moisture. LIDAR data exists from many parts of the EU; however, it is not included in the models because the models are based on propagation velocity. So, while LIDAR is significant, there are still issues to be resolved, as described in the previous paragraph.

Available data

Collecting data helps us to check and validate hypotheses and also to make new ones. When approaching data collection there are important aspects to consider, as, for example:

a) the importance of historical fire data to compare with the current ones and anticipate future ones;
b) the importance of the context in which the fires take place (previous conditions).
c) the importance to have open data, accessible and global, suitable for upscaling.

It would be really useful to have a common database where everyone could have the data of fires occurred regionally and learn online, however data should be collected in a more or less standardised manner. This database could include real cases and meteorological information linked to the fires in order to better understand the connections between fire and the atmosphere. It could also include cases based on unpredictability, which happens often during the fire season, to look for answers to real cases and observations.

But it is vital to realize that the process of acquiring data can take time, especially if we want it to be robust and the phenomena is not frequent. At the same time, it is important to work on solving the existing challenge, even if the desired information or all the data that would be desirable is not available to make the solution fully robust.

Often, while making decisions, not all the present information is needed as long as the crucial information is available, even if it is scant.

When approaching the study of EWE, while waiting for as much information as it can potentially be, work should be done with the existing data to ease decision making. This is of critical relevance because as EWEs will continue to occur and responders and society will have to face them. It is necessary to work on what is already available now or at the moment of the event while we approach to gathering enough information to have robust data from a research point of view.

EWEs and self-protection

Self-protection measures include containment and evacuation, and its application responds to different criteria depending on the region, such as the possibility of safe confinement from fire impact, the possible evacuation time, evacuation capacity and practice, etc.

Self-protection structures have worked in fires that advance by the flanks or from the back of the fire. But to be useful, they have to be designed in accordance with the expected fire conditions, considering the propagation to know how the fire will move on the landscape and not just the amount of vegetation fuel.

Appropriate building materials are being investigated to improve fire protection. To find out which materials are more fire resistant, laboratory analyses are often carried out. **But EWE conditions cannot be reproduced on a small scale in laboratories**.

Summary of guidelines - EWE

Key variables to identify and predict scenarios

- ✓ EWE appears with little wind and a lot of humidity.
- ✓ In pyroconvective episodes, ambient humidity trigger extreme fire behaviour.
- ✓ Extreme fire moments happen at night.
- ✓ There is a need to focus on what is unexpected.
- ✓ It is also important to find how much energy it will be transferred from the fire to the kinematic of the fire plume.
- ✓ The Growth rate (S/ha) and ROS are key variables to describe the extreme fire behaviour and growth patterns of these fires.

Models

- ✓ Existing fire models are based on input assumptions, but in reality, a surface meteorology and fuel availability is being modified by fire-atmosphere interaction. For high intensity fire we need to focus on coupled models.
- ✓ Simulators integrating coupled fire-atmospheric processes are not powerful enough to be used on the field at the moment
- ✓ Develop good new models to explain EWE processes or to validate hypotheses.
- ✓ Definition of the key parameters to include in the model for operational decision-making.
- ✓ Focus on key variables to make decisions of fire behaviour such as ROS and growth rate (S/h).

- ✓ Some key processes on the physics of fire behaviour need to be better understood.
- ✓ Real extreme fire events information is crucial, but a good operational understanding of local fire types, challenges posed, fire spread patterns, etc. is needed.
- ✓ Focus on 'WHEN' the PyroCbN could appear.
- ✓ Research on coupled physics as well as focus on fire spread processes (improve good fire perimeter position forecast already provided with today's tools) are the hot topics for improving simulation capabilities and confronting EWE in the near future.

Indexes

- ✓ Development of reliable indexes focused on 'WHEN' an EWE may occur.
- ✓ Valid solutions at all levels should consider the scales of application.
- ✓ Large-scale indexes seem to perform worse than locally adapted indices.
- ✓ Real radiosonde profiles based on what is happening vertically in the atmosphere.
- ✓ Boost discussion on adaptation or creation of new ones.

Identification of key variables and the level of detail

- ✓ Identify the key variables for EWE.
- ✓ Integrate the key variables into the models and adjusting them or creating new ones.
- ✓ Invest on getting real time data during EWE and be prepared to take this information.
- ✓ Create global database to identify global patterns and apply statistics.
- ✓ Integrate the structure of the vegetation into simulations/models.
- ✓ Define the level of detail the models need to integrate the soil moisture.

Available data

- ✓ A common database of fires that have occurred regionally and meteorological information could be useful.
- ✓ Data should be collected in a standardised way.
- ✓ It is important to work on solving the existing challenge with the current available data to enable decision-making, even if it is not the desired amount of data necessary to be as robust as desired.

Safety areas

- ✓ For self-protection structures to be useful, they have to be designed in accordance with the expected fire conditions, considering not only the fuel amount but how the fire will move on the landscape.

FIRE-RES Innovation Actions contributions

The FIRE-RES project tackles some of the challenges and gaps highlighted above through the following Innovation Actions. This section seeks to contribute to examine that the Innovation Actions address the existent challenges specified in previous sections and fill the gaps.

During WS1 some of these innovations were addressed directly, some indirectly and some were not addressed at all. The most significant points are presented below.

This section is not intended to describe the innovations directly; this description has already been done in other documents. In this section, the key principles that should guide the work in the IAs are presented as a framework for the steps that should be taken in the future.

After having analysed the issues and holes in previous sections, this section focuses on specific IAs to guide IA leaders on the needs, lessons learned, what has worked and what has not, etc. for each of them.

Table 1. FIRE-RES Innovation Actions linked to the EWE process/behaviour drivers' pillar.

CHALLENGE/GAPS	TOPIC	INNOVATION ACTION
Key variables we should monitor in order to be able to identify and predict risk scenarios	Landscape	**IA2.1.** Improving data acquisition for landscape design based on novel remote sensing methods (ICGC, NIBIO)
	Atmosphere	**IA1.2.** Testing key inputs for atmospheric data analysis using new knowledge and expertise on EWE (CFRS, CONAF)
		IA5.5. Testing **of vertical atmospheric structure models** based on satellite constellation in EWE (SPIRE)
	Energy Fire Behaviour	**IA5.2.** Demonstration of real-time EWE simulation and smoke spread based on coupled fire-atmosphere approaches using of HR weather data (TSYLVA) **IA5.3**. Advanced vegetation characterization based on Earth Observation data fusion and Artificial Intelligence over forestland ecosystems (ICGC) **IA5.4.** Piloting models for fire combustion and Pyrocumulonimbus with use of HR data (VTT)
Capacity to collect real time data both at an appropriate scale, and also vertically in the atmosphere.	Earth Observation	**IA5.5.** Testing of vertical atmospheric structure models based on satellite constellation in EWE (SPIRE) **IA5.6.** Prototyping HAPS (High Altitude Pseudo Satellites) contribution to Europe's resilience against EWE (AIRBUS)
The current protection measures for WUI do not work for EWE.	WUI	**IA2.3.** Defining recommendations for improving security on WUI at multiple scales (CNRS, ISCI) **IA4.4.** Fire-safe villages (XUNTA) **IA5.7.** Quantifying impacts of exposure to air pollutants from wildfires (CSIC, INESC TEC, ANEPC, FWISE)
The mathematical models (algorithms) of the simulators do not adjust to reality, they do not represent it.	Models/simulations	**IA5.2.** Demonstration of real-time EWE simulation and smoke spread based on coupled fire-atmosphere approaches using of HR weather data (TSYLVA)

CHALLENGE/GAPS	TOPIC	INNOVATION ACTION
We do not have the capacity to anticipate the EWE. E.g., even with the current indices.	Indexes	**IA1.3.** Piloting early-warning indicators of EWEs incorporating fire-weather and vegetation conditions (INRAE)

Note: In blue there are those IAs that can be included in more than one theme or challenge.

Emergency and fire management

This section is based on the discussions and highlights about 'EMERGENCY AND FIRE MANAGEMENT' challenges and gaps' with the next participants: Andrew Elliott (Dorset & Wiltshire Fire and Rescue Service), Edwin Kok (Nederlands Instituut Publieke Veiligheid, NIPV), Enrique Eduardo Fernández (112 Madrid), Francesc X. Boya (CFRS), Jordi Brull (CONAF), Jorge Saavedra (CONAF), Marc Castellnou (CFRS), Mario Silvestre (ANEPC), Núria Iglesias (CFRS), Xavier Joseph (SDIS13, Pompiers Bouches-du-Rhône).

Lessons learned

Organizations that face new and challenging situations develop the ability to innovate and adapt in order to cope with the change. Emergency managers are not an exception. They frequently require solutions to the challenges they face, and they require these solutions as soon as possible, usually before the next fire season, because they cannot wait years to find solutions to deal with the potentially fatal consequences of extreme wildfire events and the need to respond today.

This section aims to provide some examples of lessons learned, adaptations and changes, as well as gaps that still exist. The FIRE-RES project focuses on innovations to address EWE, so it is important to be clear about where the efforts might be in order to focus on what is new and what is a real step forward. This section aims to show the existing framework and to share the same vision and show what questions and gaps are still unresolved. At the end of the project, it will be possible to assess whether a significant contribution has been made to solving some of these gaps by comparing the final results with the existent framework described in this D1.1.

It is important to invest efforts in going beyond the existing solutions. Knowing what already exists allows us to go one step further and it is precisely the challenge of this project to deal with the EWE.

Portugal 2017

In 2017 fires, there was a problem of simultaneous fires, one of them in Pedrógão Grande, with a really high rate of growth and extreme behaviour as mentioned before in this document. There was an incapacity to predict the fire behaviour at that moment and a lack of capacity to command and control.

At that moment in Portugal the incident command system (ICS) had 4 level and after 2017 it was increased to 6 levels. Until 2017 the system was prepared to manage approx. 650 firefighters of operational personal, but then the number raised to 1000 firefighters. The system was improved after 2017 and now it has the capacity to manage 2000 firefighters in a fire. This has involved changes in the operations management system.

In Portugal, fire analysis is at national level, so when there is a fire, even a small one, they include the support team from the first operational period of the fire to perform the analysis. Then they can add airplanes with cameras to take pictures, videos, infra-red pictures, etc. that are useful for the analysis. That information is transferred to the field and to the incident command (IC) on-time. When the event is going to escalate to a huge fire, the analyst is integrated in the planning cell, in the command post, in the Incident Command Post (ICP).

Some of the biggest problems detected in the fires of 2017 were:

1. The incapacity to predict fire behaviour.
2. The loss of command-and-control capability.
3. The loss of operational management capability.
4. The lack of credible information and its availability on time.
5. Too much noise in the information, which was wrong or outdated.
6. Lack of ability to transmit orders to operational sectors.
7. Lack of logistical capacity to keep operatives in combat.

Fig. 21. Forward Command Post after 2017 fires. Source: Mario Silvestre (ANEPC) from his presentation for FIRE-RES WS1.

The needs detected in the 2017 Portugal fires are listed below:

1. Information management systems
2. Georeferencing of all means in the field of operations
3. To increase the analysis capacity
4. To increase the capacity to integrate and collect data
5. To have the capacity to modulate fire behaviour
6. To have a common operational picture. The above 5 points aim to have a common operational picture to support the decision-making and are based on real time operational information (on-site, aerial means, terrestrial means georeferentiation), geographical information, between the fire assessment area and the operational area, decision support, at different levels (example: National, District, etc.). All the information is collected and transformed in decision-making support tools that include information about the fire, characteristics, etc.

Fig. 22. Public information available during a fire. Source: Mario Silvestre (ANEPC) from the presentation of FIRE-RES WS1.

Catalonia

CFRS has evolved and taken a significant step forward in its support of incident command (IC) in recent years.

There has been an evolvement of the analysis team to make easier for the IC to have the best and updated information for decision-making. Some of the positions of this analysis team are on-field, inside the Incident Command Post (ICP), which means being on-site where things are happening and allowing the IC to have the best information about the fire evolution, spread evolution and about where the fire will be in the next hours. This information can contribute to decide about what is more important at each moment.

There has been an evolution also in the planning area. There is monitoring of all the people deployed on-field by following their radio positions using GIS and radio network tools. This monitoring facilitates the evaluation of safety which is really important due to the inherent uncertainty of these EWE situations, and it gives also updated information (fire perimeter evolution, on-field images and information, etc.).

Improvements in analysis and planning are key elements in defining the strategy and the tactical objectives and sharing both information with all teams deployed on the ground specifying what needs to be done in the coming hours.

It is not an easy job because it is difficult to circulate the information to every firefighter on the field, considering the number of firefighters and the size of large forest fires and EWEs. This information can also be circulated to other agencies (police, paramedics, etc.), so all of them receive the same information and know the plan, the risks, the area with active work, etc.; with the politicians and with the media, to inform the population. All this helps the IC to manage the emergency because explaining the plans and goals boosts trust and facilitates the work.

France 2016

In 2016, a huge fire in France gave some important learning lessons to deal with such fires that emerged from the experience in it.

1. **Simultaneity**: Challenges appear with simultaneity when there is a big fire, and a second fire starts because resources are limited. Organizations are used to face a single big fire but when it becomes huge is usually when there appears a second fire. The first big fire usually requires a lot of resources, and when the second fire starts it may happen that there are not enough resources, and it becomes a huge fire. Therefore, **it is important not only to know how to predict but also to predict when the situation may lead to simultaneity** or which of the simultaneous fires may generate an EWE, and which may not.
2. **Crisis communication**: The fire was running more than 4 km/h and more than 40 houses burned. Usually, **when there are houses burned in that region there are legal actions** after the fire and firefighters are questioned about actions to save the houses. For this fire, the organizations' communication changed and avoided **legal actions** after the fire. They **used a more outspoken communication, telling people that they were overwhelmed, that the situation was not under control, and that there may be many casualties. So, people were more prepared to see the consequences**.
3. **Tactical situation tool**: From such fire experience, they implemented **tactical situation tool** which makes them able to share in real time the tactical situation on-line. They also use **airplanes with cameras that can provide live streaming** information to the operational centre ICP (Incident Command Post) or directly to the wildfire analyst. Such life-streaming also provides **infrared pictures and drawing the location of the fire** in real time because one of the main questions for them in this kind of incident is to know where the fire is.
4. **Legal action: the policy**. As they had started in 2000 to make a kind of prevention plan for wildfire hazard, after this big fire it was decided to prescribe this kind of plan to every municipality. This plan is built with the fire service and has important consequences on the capability of building houses or developing new houses in areas that are directly exposed to wildfire hazard. Using this tool, if a place is under a high risk of wildfire, the municipality cannot allow houses to be on this place.

The Netherlands

Highlights of The Netherlands situation are described below:

1. **Raise awareness**: In the Netherlands, wildfire management was started approx. 10-12 years ago, before that there were no fire problems. In 2010 there were some big wildfires and in 2020 they had two big wildfires for their standards, with the largest fire at peat area. That was a turning point but the fact that it often rains does not help to increase awareness in front of wildfires. This forces to communicate frequently that the focus must be in the future not on what is

currently happening. They have experienced large wildfires and can predict that they will come again so there is a need to be prepared for them.

2. **Means and resources (internal and external):** Simultaneity is also a problem in The Netherlands. They have already experienced this situation. They have faced several fires at the same time (2–3) and it has become clear that it is important to address the problem in order to avoid collapse. With two simultaneous fires it was clear that if a third one appeared there will not be enough resources to extinguish the fire. The EUCPM can be an external resource to consider but there is a lack of experience in host nation support.
3. **Several stakeholders:** There are several Ministries that are involved in wildfire management. There is a working group to discuss the responsibilities, because there is no legislation in the Netherlands regarding wildfire management or limiting buildings in wildfire risk areas. So, the working group aims to include organizations to define the problem and the solutions. The Netherlands Fire Service works together with other organizations, basically nature managers, the meteorological institute, provinces, municipalities, and government, to improve the situation. Contacts with other organizations already existed before 2020, but the 2020's fires boosted the conversations.
4. **Prescribed burns are not socially accepted**. In the Netherlands, people do not want any fires in the nature. So, civilians want every fire to be extinguished in a short time and prescribed burns are not common. There are two challenges regarding prescribed burns: most civilians do not accept fire in the nature (pollution, possible danger), and legislation, which only allows to use very small fires (<0,5 hectare) for prescribed burns.

Communication

CFRS

The Cabinet Press of the Catalan Fire and Rescue Service (CFRS) is a communication team integrated in the CFRS since 1994, when they understood that CFRS had to communicate directly to the population.

1. Some of the challenges from the **emergency management communication** perspective are: The lack of predictable entrainment information during the events, the need to deal with too much noise about information and the crisis communication.
2. **The information and the communication have to be managed always** (before, during and after the event) and not only during the day of the event when under pressure. If it is not done, two fires appear: the wildfire and the media one.
3. **Both good news and bad news must be communicated, because population should rely on the organization**. The communication should not only include the things that the organization want to communicate when the situation is under control but also when there are difficulties or when it is no clear when the wildfire will be controlled. This communication has to be managed from inside the

organizations and then translated (managed and transformed) to the politicians, to other agencies, and to the media as well.

4. **It is important to translate the information to the target language**. The translation has to be done always (before, during and after the event so this can last weeks) and using a plain language. At the moment of the wildfire, the population may feel in danger, there might be a social alarm, and if journalists do not get answers, they will be working to find other speakers. As an emergency manager, it is important to always keep the population informed and lead the discourse to avoid noise.
5. **Getting the population to accept prescribed burns (PBs) is difficult and slow, so it requires long-term work**. It normally requires fighting against social and cultural issues, so it is a very slow job but it works. People, especially from urban areas, perceive the fire as a problem, as a disaster. So, it is important to explain why the prescribed fires can be beneficial. One might think that in the Mediterranean areas they are well used to fires because there are fires each summer. But the CFRS service introduced the prescribed burns in 1998-1999 after two major fire crises. In the '90s they only used hoses and realized that the fire was faster than the capability of the organization to extinguish it. So, at the beginning of 2000, CFRS acquired the capability of making prescribed burns and technical fires to stop the fire. But it was quite shocking also inside the organization, because fire was always perceived as a negative thing. It is important to invest time in explaining the benefits. But the organization needs to be reliable, so it cannot make a PB and fail.

112 Madrid

From an Emergency Centre point of view, a huge wildfire is not a big problem in relative terms but the huge number of calls when a wildfire lasts several days and people do not get the information and they call to the 112 it is a challenge because they use the 112 as an call information centre instead of a call emergency centre increasing the amount of non-urgent calls received. So, it is essential that people receive the information periodically.

In 112 Madrid, there is a team of five journalists exclusively dedicated to the emergencies, but they cannot inform the population if they do not receive the information from the politicians and from the staff who is in charge of the emergency.

CONAF - Chile

In Chile, after a fire storm they have been working on supporting the IC through simulation results to facilitate decision making. The fire simulations work but does not always offer good results. In their case, they have encountered problems when displaying this type of information to the population in the vicinity of the ICP. Often, the population demands to know where the fire will be stopped which means to inform where they are allowed or forbidden to be. The CONAF experience is that it is better to display information only in crisis cabinets and not extensively. On the other hand, it is important to have another space, different from the ICP, where people can go to ask questions and seek information. They made a simulation in Valparaiso in 2021 in La Engorda Fire Complex which burned 4.000 ha, and the evacuation involved 20 thousand people, and this separate division (ICP vs information post) worked.

Information and noise

The Netherlands

In the Netherlands they filter the information and consider it to be working appropriately. They have a common operational information system, including all the emergency services involved, where they can share information. They also have an information officer. But the problem they are facing is that most of the information is correct but it is outdated because of the long process of data management. First you have information, then you have to discussed about it, and especially if it is about wildfires, an hour later the situation may have changed completely. They are working on the next items:

1. Shortening the time between getting the information and having it ready to make decisions.
2. Trying to have a drone always flying above the incident, and to have a person who is always watching the recording, seeing what actually is happening, plotting the fire-line. It is in the pilot phase.

112 Call centres

112 call centres also face this challenge. The first group of calls is important and checklist is a tool to gather information. In Madrid 112 they use a checklist to get the important information, this checklist is shared with the rest of emergency services. It is not always possible to get the best and complete information to send to the emergency services, because it depends on the person that is calling. The profile of the person who is calling influences on the information obtained.

Challenges from response perspective

General challenges detected from 2017 Portugal Fires

From the 2017 Portugal Fires there are challenges not yet solved which are listed below:

1. Better prediction and modulation tools.
2. Integration in the modulation that they are already using: treetops fires (crowning), spot fires, and the effect between two fires.
3. Integration in the modulation (models), the effect of the suppression actions – in progress and those foreseen; if I am putting guides fighting the fire, what is the effect?
4. Better interoperability between all systems.
5. Better risk communication.
6. Reinforce inter-entity communications/cooperation.
7. Improve the education of the population.
8. Common operational picture, in all the fires.

9. To improve prevention and resilience of all the potentially affected populations and infrastructures.

Emergency management

Specific challenges have been identified for this topic:

1. **Cross-services**: These kinds of operations need several services to be involved (police, municipalities, other ones) so it is important to have a kind of inter-service cell. If this cell is near the ICP, the IC can discuss and mobilize everybody around the problem.
2. **Interoperability**: In France, in a huge incident like EWE, they have more than 1000 firefighters on the field coming from all around the country, and they need to be able to work together, speaking the same language. National schools can help with this, so every IC that deals with wildfires could be trained in the same place in the same way at the national level. We should develop interoperability at the regional/national level and maybe also at the international level.
3. **It is easier to simulate urban fires than wildfires/EWEs in real conditions**. All the theoretical knowledge can be addressed but experience and skills are also needed to be well prepared. In the Netherlands, the 99% of fires are very small so it is a challenge to train people who have not seen big fires. One solution may be to boost the exchange of information and knowledge, and the exchange of experts between countries.

4. **Training** organisations are pushed to have more realistic training contents. The design of the training simulations introduces the parameters that are known so the software will give known behaviours. But to address the EWEs and their unpredictability is a challenge.

   Virtual Reality (VR) videos could be used (e.g. https://youtu.be/tObUvHXSTRk for Pedrogão in VR 360 video). But at the moment, computing resources required are still too high to be considered. In 2017 in Portugal, it would have required 4 times 300 processors (4 large wildfires for 24 hours of propagation), with a refresh every 12 hours and high economic costs.

Information and noise

Information is vital for decision-making, but it has to come from people who know all the existing implications involved and repercussions. Otherwise, that sort of information does not add any value but only pressure on emergency management. It is essential to have information without noise. Some of the obstacles ahead are:

1. **The use of tools that are not validated for the scenario taking place should be avoided**. It is important to avoid the use of models for which it is not known whether they are useful for the specific phenomenon to be addressed, in this case the EWE. The validity should have been checked before using them during the emergency. It is important to set a red line between what is information and what

is pressure on the system. It is of paramount importance to remember that to give information involves a responsibility.

2. **To have a defined structure and flow of information**: In some organisations a lack of a defined structure and flow of information is seen as a problem of structure, i.e., when information flows through unestablished channels and gets mixed up with other information, e.g. strategic people interfering with operations. Some of the solutions currently ongoing under this scope are:
   a) The use of **public information officers**, to whom they filter all the noise from the media that is useful for organisations. But this is for general information because it does not have the aim to inform the commander.
   b) A **clear delineation between roles**.
   c) Multiagency work with a representative for each organization.
3. **Information does not arrive at the speed necessary for decision-making or it arrives outdated**. Sometimes when the information arrives, most of the information is outdated, and the situation has changed completely. It is important to shorten the flow of information, to be able to know at each moment where the fire is and detect changes.

Guidelines

Incident commander and fire analyst capabilities

Firefighters are accustomed to working in wildfires, but fire behaviour is evolving. Because EWEs are not the most common at the time, there aren't many opportunities to gain experience dealing with them, therefore training becomes essential to be prepared.

1. **The Incident Commander (IC) and the Fire Analyst (FA) must be integrated**.
2. **The IC and FA must understand each other**. This understanding includes language and needs. The IC not only focuses on analysing the fire but has to also take into account other aspects of emergency management (logistics, communication, etc.).
3. **The IC needs to be able to call for help when the fire is going too big**.
   So, one of the solutions used is **to increase the command system**. This means to have several people on the background working together with incident command and having a fresh image on what is happening and looking for opportunities. The aim is to have **teamwork with the same strategical vision and tactical goals**.

   In some organizations, the head of the incident is supposed to deal with the incident on his/her own, even if it gets bigger than expected. It is important to call for to help to avoid the tunnel vision phenomena. For example, in the Netherlands when there is a large fire or large incident, they call for a second officer, or third officer, who is only responsible for making the plans after the first 4–5 hours, and then there is a change in order to maintain fresh personal for the next phase of the incident. The procedure foresees that if the objective is not achieved in the first 5–6 hours, the call for help is required adding a second team to the main one.

They will be looking for the situation in 5-6-10 hours the next day to manage the remaining or ongoing part.

4. **The IC must be able to work with the planning, the logistical, and the operational sections making strategical plan of actions**.
5. **It is important to be able to stand back and observe**. Looking at what is happening now, and understanding that situation:
   a. To be able to look at what is happening now but **consider other immediate safety concerns to address both, for firefighters, for public or for landscape**, to listen to everybody who is out there like firefighters, land mangers or other agencies.
   b. To have the **ability to recognize the limitations** (of resources, of your own skills, etc.).

   The FA team should be **focused on looking forward, foreseeing what can happen in the next hours** and assessing the actions required (evacuate populations, protect some houses, stop, and wait to work into another opportunity, etc.). So, it is important to maintain this future vision and **not try to respond to everything**. It is important to be strategical and sometimes accept that nothing can be done at that moment and wait until the next window of opportunity. Working with this vision improves the safety in the emergency, both for the firefighters and the population.
6. **IC major role is to assure that the team is able to work without extreme pressure**. In this kind of events where there may be deaths (firefighters and civilians) the pressure is huge in the ICP (politicians, media, etc.). The IC should be able to deal with the situation and let the operational, logistical and analysis team work together to arrange and plan the action.

Communication

There are different types of communication:

1. **Internal**: communication inside the organization.
2. **External**: communication outside the organization:
   a. with other organizations
   b. with society.

These three ways of communication have different targets, different channels, and must be managed. Because if other stakeholder different from emergency managers manage this information, this can create conflicts. It is important to manage the information and avoid conflicts.

Internal communication

Some organizations are usually trained in external communication during the event, but not as much in internal communication.

Firefighters need information about what is happening, because if another fire starts, the two fires may share the same behaviour. In addition, if crews know the strategy and tactical to be achieved it would be easier for them to identify which information is useless or important. They also do multiple tasks on-field during an EWE, so information must be provided to them because they must know what is happening as they are in direct contact with the population.

In addition, specific information should be provided to firefighters who are not active at the time of the fire but who are due to join the following shifts, so that they do not only have the information from the media.

External communication with other organizations

To avoid the collapse emergency management systems, organizations can call for help from other organizations. There are specific communications that could be shared with other agencies in order to receive help from others, when the organization realizes that is overwhelmed and approaching the point of collapse. This is one of the actions that the project wants to explore (WP5) and develop tools for exchanging information at international level with other stakeholders, fire analysts, networks, with other IC, etc. looking for advice and help.

External communication with society

One of the questions we need to ask in addressing communication is what information should be communicated and what information does not need to be communicated, when, how, and who talks to the population.

1. **Organizations must be able to manage the communication meanwhile they are coping with the EWE**. External communication is important and must be done during the extreme wildfire events. It is a sensitive topic during these EWEs. Communication teams within response organisations can be very useful to manage information to facilitate the operational area to keep their focus remained on the response to the EWE.
   Example: In CFRS there are six journalists and three image managers, and if something happens, they join the firefighters on-field and instantly manage communication from the first minute of the wildfire.
2. **Information must be translated, and it is important to avoid noise**. It is an effort to manage communication, but it must be done. This task must be done with people coming from the communication world, because it is important to translate response languages, data, or pressure, the way of talking inside to the outside, to the general public; and to filter information to avoid noise to transfer to the command system only the important ones.
3. Organizations should be able to explain what is happening (good and bad news) in order to gain **transparency and trust**.
4. **Communication during the preparedness** phase is highly important because if population is well prepared, it will make the incident management easier.

5. Regarding technology tools, there is a challenge on **how to reach population that has not a mobile phone** during an emergency and only uses traditional means. Some organizations (e.g., 112 Madrid) use phone applications (APPs) for alerts, but they are not massively used.

Monitoring

Any sort of **monitoring** gathers a huge amount of information but only a part of it is useful for the incident commanders. So, it is important to filter information and define the key ones that facilitate decision-making.

There are different ways to monitor the EWEs:

1. The monitoring of key parameters should be directly linked to the sort and characteristics of these parameters (for more information see section *Key variables to identify and predict scenarios*).
2. Monitoring sensors or **wearable sensors** in different places (firefighters, truck, fixed ones, homes…) are planned to be used, to propose protocols for evacuation. But it would be important to think about what kind of information and for what use it is generated when using **personal sensors**, because there may be a dilemma where the results are above healthy values, but firefighters still have to respond to the emergency.
3. **System and location of trucks and teams by GPS** provide a common picture of the operation and reduce noise. But it is important to have all the current information and manage it because it is critical to have the key 'good information' for decision-making.
4. There are monitoring systems that cannot be used throughout the wildfire. For example, the use of **drones during the night** can be useful but during the day its use is limited. But for safety reasons, they usually are not allowed to fly if there are other aerial means working around in the same area.
5. The monitoring of **efficiency of water uses** and the differences between teams would be a good information to distribute to commanders using a platform in order to facilitate them to make decisions on operations when e.g., the spend of water is high.

Summary of guidelines - Emergency Management

IC and FA capabilities

- ✓ The IC and the FA must be integrated and understand each other.
- ✓ The IC needs to be able to call for help when the fire is going too big. One of the solutions used is to increase the command system and develop a teamwork with the same strategic vision and tactical goals.
- ✓ The IC must be able to work with the planning, the logistical, and the operational sections when making strategical plan of actions.
- ✓ It is important to be able to stand back and observe. The FA team should be focused on looking forward and foreseeing what can happen in the next hours.
- ✓ IC's major role is to assure that the team is able to work without extreme pressure.

Communication

- ✓ Internal communication should assure that firefighters know about the current fires, the strategy, and tactics, when they are active or before a shift, and to make them able to do their work but also inform population if necessary.
- ✓ External communication with other agencies should contribute to avoid collapse by looking for external help but also to build trust and interact with other agencies.
- ✓ External communication with society:
  - Organizations must be able to manage the communication while coping with the EWE.
  - Information must be translated to be understandable by other groups, and it is important to avoid noise.
  - To boost transparency and trust.
  - Communication during the preparation phase is highly important.
  - It is important to consider different communication channels to reach all the population.

Monitoring

- ✓ The monitoring of key parameters should be directly linked to the sort and characteristics of these parameters (for more information see section *Key variables to identify and predict scenarios*).
- ✓ When considering the use of personal sensors, it is important to think about what kind of information and for what use it is generated to avoid dilemmas.
- ✓ It is important to have the key information useful for decision-making when using system and location based on GPS.
- ✓ There are monitoring systems that cannot be used throughout the wildfire due to operational constrains.
- ✓ Monitoring the efficiency of water uses can be useful.

FIRE-RES Innovation Actions contribution

The FIRE-RES project addresses some of the challenges and gaps discussed above through the following Innovation Actions included below. This section aims to contribute to the analysis that the Innovation Actions address the existing challenges defined in previous sections and fill the gaps. During WS1 some of these innovations were addressed directly, some indirectly and some were not addressed at all. The most important points are described below.

This section is not intended to describe the innovations themselves. This description has already been done in other documents. In this section, the relevant points that should guide the work in the IAs are included as a framework for the steps to be taken in the future.

After analysing the challenges and gaps in previous sections, this section aims to address specific IAs to guide IA leaders on the needs, lessons learned, what has worked and what has not, etc. for each of them.

Table 2. FIRE-RES Innovation Actions linked to the Emergency Management pillar.

CHALLENGE/GAPS	TOPIC	IA/ACTION
Distinguish between information and noise.	Information during emergencies	**IA5.9.** Tools for international collaboration through shared operational information for specialized stakeholders (CFRS)
	Communication during emergencies	**IA4.8**. Demonstrating strategies and tools for smart communication to citizens (TIEMS) **Action**: Training on EWE for journalists (WP7)
Skills and Capabilities for EWE	IC skills & capabilities	**IA5.8.** Prototyping and testing innovative tools for EW ICS training certificates (ENB)
	FA skills & capabilities	**IA5.9.** Tools for international collaboration through shared operational information for specialized stakeholders (CFRS).
Civil Protection, responders, self-protection measures, responsibilities	Civil Protection (self-protection measures, responsibilities, etc.)	**IA2.3.** Defining recommendations for improving security on WUI at multiple scales (CNRS, ISCI)
		IA4.2. Testing a new methodology for risk communication to improve WUI homeowners' culture of risk (FWISE) **IA4.4.** Fire-safe villages (XUNTA)
		IA5.2. *[Demonstration of real-time EWE simulation and]* **smoke spread** based on coupled fire-atmosphere approaches using of HR weather data (TSYLVA)
Interoperability	Interoperability	**IA4.7.** Testing an Interoperability evaluation tool (TIEMS) **IA5.9.** Tools for international collaboration through shared operational information for specialized stakeholders (CFRS).
Decision-making in EWE	Decision Making tools adapted to	**IA1.1.** Piloting an adapted Forest Fire Potential Polygons methodology to improve decision making on EWE (CFRS)

CHALLENGE/GAPS	TOPIC	IA/ACTION
	EWE to cope with uncertain scenarios with low predictability.	**IA 5.1.** Demonstration of an integrative umbrella system for estimating EWE risk and impact in real time with HR weather data (TSYLVA) **IA5.9.** Tools for international collaboration through shared operational information for specialized stakeholders (CFRS).
		[**IA2.5.** Designing strategic networks of managed areas to improve suppression efforts against EWE (CTFC)]

Note: In blue there are those IAs that can be included in more than one theme or challenge.

Fire resilient landscapes to EWE

In the grant agreement, FIRE-RES interprets resistance as a measure of the degree to which the ecosystem or ecosystem variable is changed from its equilibrium state following a disturbance (i.e., the greater the change, the lower the resistance and vice versa), while it interprets resilience as the time required for a perturbed ecosystem or ecosystem variable to return to its equilibrium value (i.e., the less time it takes to return to its equilibrium value, the greater the resilience).

The goal of the workshop was to reach a common understanding (or even a working definition) of what "fire resilient landscapes" are. The idea was to identify lessons learned regarding this concept from different perspectives and broadly define challenges of designing resilient landscapes to wildfires and extreme wildfires events (EWEs). The discussions were organized around the following topics:

Topic 1. Ecology and landscape management

Discussions about fire ecology, wildfire scenarios, forest and landscape management for fire risk reduction, adaptive management, ecosystem services integration with fuel reduction goals, wildland urban interface resistant design, or post-fire restoration were tackled.

Topic 2. Fire as a management tool

The effectiveness, constraints, and challenges of the use of fire to create fire resilient landscapes were discussed. Three different uses of fire were addressed: traditional, prescribed, and managed fires ('let it burn' or 'resource objective wildfires'). Resource objective wildfires refer to use unplanned ignitions to achieve resource management objectives.

Topic 3. Economic aspects of resilient landscapes

The topic session discussion was about the need for mechanisms that use efficiently the scarce resources while simultaneously maintain a desirable level of ecosystem services and reduce the likelihood of future losses. The discussions addressed economic variables shaping fire resilience and the design and constraints/challenges of economic instruments (indirect/value chain-oriented or direct/incentive schemes) for facilitating the viability of the resilient landscapes.

Topic 4. Governance and risk awareness

Issues regarding the need of collaborative and systemic risk governance for dealing with, achieving, managing, and maintaining more fire resilient landscapes across rural Europe were addressed. Governance and risk awareness were approached from the following perspectives: stakeholders' engagement, institutional wildfire risk management and planning, and the planning and governance process itself. Risk culture and awareness was brought to the discussion by exploring the landscape social dimension focusing on fire culture, vulnerability, and resilience.

General scope

The concept

The concept of resilience has been defined, interpreted, and approached in a variety of ways. Holling (1973) introduced the classic concept of 'ecological resilience': "*A resilient ecosystem is one that can 'absorb' disturbance and maintain a qualitatively similar state.*" This concept of return to baseline has been the predominant approach to studying and/or defining resilience. Similarly, Walker et al., (2004) defined resilience as "*the ability of a system to absorb disturbances and reorganize itself while undergoing change so that it retains essentially the same function, structure, identity, and feedback*". Nonetheless, Walker et al., 2004 argued that the stability of a socio-ecological system emerges from three complementary properties: resilience, adaptability, and transformability. Adaptive capacity is defined by Walker et al., (2004) as "*the capacity of actors in a system to influence resilience.*" That is, the system adapts to new circumstances. Transformability is defined as "*the capacity to create a fundamentally new system when ecological, economic, or social (including political) conditions make the existing system unsustainable*" (Walker et al., 2004). As natural disasters have occurred more frequently in recent years, communities, managers, and policymakers have set goals that emphasize transformative or adaptive resilience rather than basic/classical resilience. (McWethy et al. 2019). McWethy et al. 2019 adapts the concepts of basic, adaptive, and transformative capacity to the wildfire context.

During the workshop, all of these definitions were discussed and debated but one of the important themes that emerged was that the architecture of the notion of a fire resilient landscape should embrace all elements of the socio-ecological system (e.g., physical, ecological, economic, or social). A multidimensional approach allows for a more realistic and relevant assessment of a fire resilient environment than using only one dimension. The challenge for FIRE-RES is to continue defining and operationalizing the dimensions of fire resilient landscapes. For instance, within each dimension, a set of monitoring parameters (e.g., fuel load availability, demographic structure) and corresponding thresholds (e.g., 10 t ha^{-1} of available fine fuel load) could be identified and used to assess/score the resilience of a given landscape to EWE. By assessing each dimension, we might be able to set targets for building basic, adaptive, or transformative resilience within each dimension.

It is worth emphasizing that for some parameters, there are currently no known thresholds for preventing the development of EWE, while thresholds for large but conventional fires could be used instead.

Furthermore, resilience may not have the same dimensions, parameters, and thresholds across northern and southern Europe. Finally, landscapes can be resilient in one dimension (for example, physical resilience) but not in another (e.g., social).

Economy, infrastructure, health, ecology, recreation, community character, agency capacity, and emergency management organizations are all factors to examine when assessing landscape resilience. The following dimensions could be used based on these elements:

- Infrastructure capacity (e.g., internet, hospitals, power lines, communication infrastructures, schools, rural grocers, roads).
- Emergency management organization (e.g., capabilities, trust, procedures).
- Economic (e.g., ratio primary vs tertiary sectors, cost of suppression businesses, forest products, locally processed products–cheese, agriculture).
- Social and individual (e.g., risk awareness, sense of place, cultural influences).
- Physical landscape configuration (e.g., landscape structure, fuel discontinuities, urban forest interface).
- Forest and ecological functioning (e.g., stand structure and composition, ecosystem services provisioning, biodiversity).

The proposed dimensions are still under discussion (see Key Task Force Ideas), but the general idea is that the concept of fire resilient landscape should be multidimensional. Fig. 23 shows one way to operationalize the concept of fire resilience based on the KTH (Kungliga Tekniska Högskolan) Innovation Readiness Level. The case shows a landscape that is resilient in terms of physical and ecological functioning and reasonably economically resilient but has low social resilience. In order to score each dimension, a list of parameters and thresholds must be established, which are then used to score the landscape under study (Fig. 23). The overall score of each dimension could be defined as the average of all parameters. Another option would be to rank the parameters according to their importance and weight them differently.

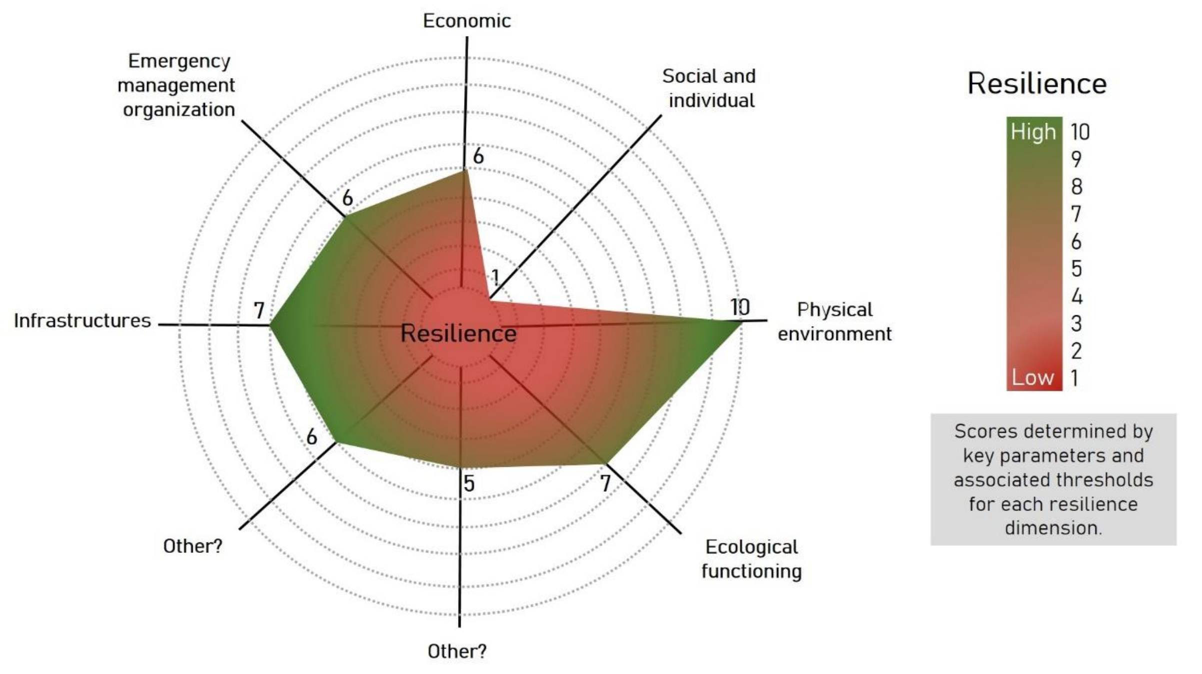

Fig. 23. Framework for guiding the assessment of fire resilient landscape status across key dimensions. Based on the KHT innovation readiness level.

Cautions to consider

- Unknown processes that drive fire spread (atmospheric dynamics) may limit the proper implementation of resilient landscapes from the fuel management point of view. Despite the weak influence of fuels on wildfire behaviour under extreme conditions, fuel management contributes to wildfire management and ecosystem resilience and resistance (Cruz et al., 2022).
- Resilient landscapes to EWEs require not only resilient ecosystems, but also well-organized emergency management organizations and effective policies oriented to sustain recovery measures, both at the ecological and social level.
- Determine the appropriate scale for integrated fire management planning.

General view of approaches for fire resilient landscapes

- In order to promote, implement and maintain sustainable landscapes, it is necessary to ensure a sustainable balance, considering all dimensions equally (environmental, economic, social, etc.). However, the centre of this sustainability will very much depend on local communities' context, conditions, and landscape management purposes.
- As approaches of fire resilience can differ between regions, we need to identify fire resilient landscapes depending on the regional characteristics.
- In general, we might get fire resilient landscapes by:
    - Changing land use.
    - Changing human behaviour/ self-organizations.
    - Seeking to reduce extinction costs with fire management.

  - Reducing forest biomass and necromass and changing how it is distributed at the landscape level (Homogeneous vs. Heterogenous landscapes)
  - Promoting the forest-linked bioeconomy and the recognition and payment of environmental services by society.
  - Correcting inequalities in the distribution of financial incentives between and within European countries.

Key task force ideas

At the initiative of the FIRE-RES coordination team and at the suggestion of the Project Management Team (PMT), a working group was established to define the concept of fire-resilient landscapes (Task force on the fire resilient landscape concept). The idea was to have a representative from WP1 to WP6 as well as members actively involved in the daily development of the project. The first online meeting was held on 17/10/2022. The following participants attended: José Ramón González (CTFC), Inazio Martínez de Arano (EFI), Elena Górriz-Mifsud (CTFC), Pere Casals (CTFC), Teresa Valor (CTFC), Lluís Coll (UdL), Eduard Plana (CTFC), Miguel Mendes (Tecnosylva), Jordi Garcia-Gonzalo (CTFC), Elena Feo (Euromontana) and Antoni Trasobares (CTFC). The following is a summary of the main ideas expressed during the first meeting:

- **Type of fires**: There was discussion about whether a distinction should be made between normal fires and EWE when evaluating resilience. The distinction between the two is important because resilience depends on the degree of disturbance.
- **Spatial and temporal scale**: It was pointed out that the ability of a landscape to be resilient is related to the scale of the territory (i.e., at the municipality scale, one may not be able to meet all challenges for being resilient). Also, metrics are scale dependent. Some participants suggested that it might not be a problem to consider more than one scale level for the different dimensions and metrics. Temporal scale was also mentioned, as a landscape may be resilient in the medium term, but not in the short term.
- **Dimensions**: Most of the discussion was centered on what dimensions should be considered. Several ideas were proposed. One was to think about capacities or functionalities of the landscape instead of landscape features (as shown in Fig. 23) and then look for some dimensions for those capacities. Another idea was to use the phases of the integrated fire management concept (response, preparedness, recovery, and mitigation) and then look for dimensions within each of these phases. Similarly, it was suggested that the dimensions should reflect what we know about wildfire and disaster resilience. For example, 1) Understanding and addressing the risk of occurrence (hazard), 2) Managing suppression with existing resources, avoiding disasters, 3) Identifying and protecting key assets (WUI, materials, evacuation, etc.), 4) Better build back, applying IFM approaches, 5) Coherent cross-sector governance to ensure positive contributions to risk reduction from all stakeholders, 6) An economic framework that promotes risk

reduction. These dimensions would allow, for example, to include all measures and metrics on fuels and suppression capacity in 2), insurance for better build back in 4), etc. Lastly, participants pointed out that the tool should be able to assess landscape resilience multi-dimensionally to understand where priorities lie, and also consider the capacity for improvement in each dimension. With this in mind, it was suggested that an "implementation capacity" dimension might be included.

- **Metrics**: it was emphasized that metrics can be either quantitative or qualitative, as it is more difficult to establish quantitative metrics for some policy and social aspects. Caution should be exercised when using a multi-criteria assessment, as some aspects may be counted twice (e.g., ecological losses can be quantified both economically and ecologically).

Fire resilience from each topic's visions

The following subsections present each theme's perspective on fire resilience, so the multidimensional approach is not considered here. The knowledge gathered during the workshop of "Fire resilient landscapes" on each topic can be used as a basis for identifying the appropriate dimensions, metrics, and thresholds.

Ecology and landscape management & Fire as a management tool

The vision gathered from topic 1 and topic 2 is that fire resilient landscapes should encompass both resistance and resilience attributes. Fire resistant landscapes are those that are able to withstand a fire event (i.e., by limiting their spread and intensity) and, as a result, generally have lower post-fire impacts (with exceptions such as underground fires that have limited spread and intensity (Kw m^{-1}) but high impacts). Fire resilient landscapes are those that are able to return to a state of equilibrium (i.e., recover) after the fire event (i.e., species and functions recover after the fire). Resistance and resilience need to be assessed at both the stand level and the landscape level, and both levels should be considered when formulating goals to build resistance and resilience (Derose and Long, 2014) (Box 1).

Box 1. Key terms for assessing fire resilient landscapes from the ecology and forest management perspective and the fire as a management tool topic.

Resistance: the ability of the ecological system to persist through a disturbance event. That is, the capacity to continue providing functions and ecosystem services after the event. In the case of wildfire, resistance could be inferred from the influence of ecosystem structure and composition on fire severity and intensity (at the stand level) and of landscape configuration (e.g., multistand structure and composition) on the rate of fire spread (at the landscape level) (Derose and Long, 2014).

Resilience: the ability of the ecological system to recover, in terms of rapidly providing the functions and ecosystem services that the system provided before the fire. In the case of wildfire, resilience could be defined as the effect of fire on subsequent forest structure and composition (at the stand level) and on subsequent proportions of age classes and on species dominance in the landscape (at the landscape level) (Derose and Long, 2014). For example, resilience can be assessed by the percentage of species with traits to recover rapidly after fire, such as species with protected buds through bark or soil that resprout after aboveground destruction. Resilience depends on the characteristics of the system (e.g., diversity of plant responses to fire), the event (e.g., intensity), and the presence of additional stresses before and after the fire event (e.g., prolonged drought, pest outbreaks, torrential rains, etc.).

The relationships between resistance and resilience can provide insight into the post-disturbance state (for example, if a forest type has both low resistance and resilience to wildfire, there will be a significant net loss of that forest type and the system may transition to a different ecological state) (Fig. 24). Thus, the relationship between resistance and resilience can help determine the post-disturbance state of an ecological unit: unaltered system, the system is able to come back to previous state, or it recovers to a more desirable new state. (e.g., full recovery, net gain, or net loss of community species diversity) and, importantly, whether that state is the result of a loss of resistance, a loss of resilience, or both (Nimmo et al., 2015). This enables the identification of ecological units (for example, species, communities...) that may require management intervention, as well as the sort of intervention necessary (whether management should prioritise building resistance, resilience, or both).

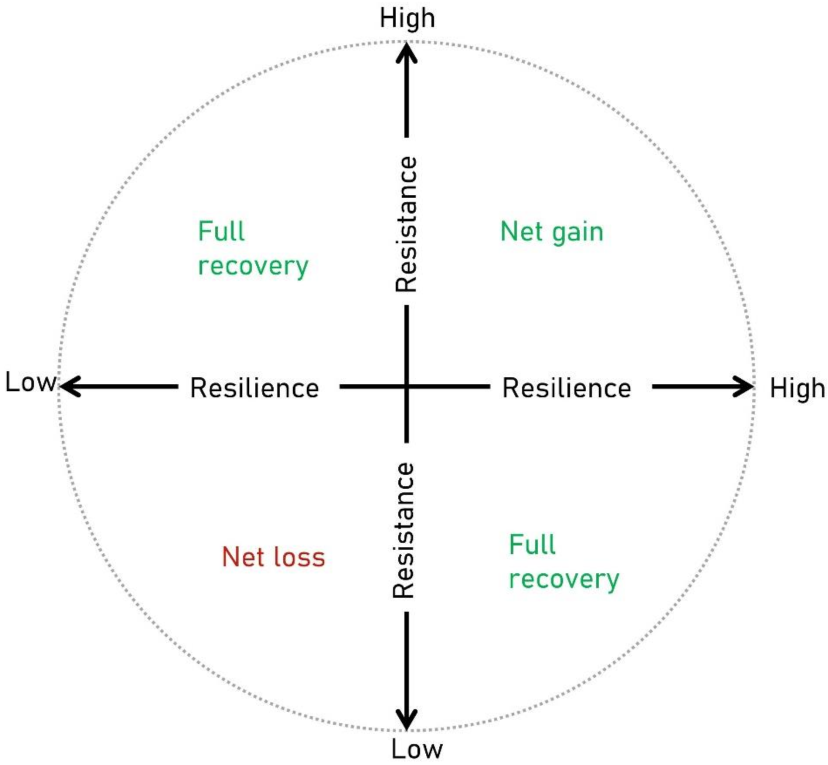

Fig. 24. Post-disturbance state of an ecological unit based on the relationship between resilience and resistance. FULL RECOVERY: high resistance and low resilience or low resistance and high resilience. NET GAIN: high resistance and high resilience or high resistance and moderate resilience or moderate resistance and high resilience. NET LOSS: low resistance and low resilience or low resistance and moderate resilience or moderate resistance and low resilience. Based on Nimmo et al. 2015.

In summary, resilient landscapes to EWE can be achieved through ecosystem-based forest management to increase the resistance during the event, short-term resilience of species and functions after the event, and transformative resilience of landscapes in the long-term (i.e., using post-fire restoration to radically change the structure of the landscape after a fire to make it more resilient to future fires through, for instance, a change in the land use).

Economics aspects of resilient landscapes

The conceptualisation of the human-nature interactions as “ecosystem services” stems from the environmental economics discipline, indicating the benefits (and consequently values) humans derive from the ecosystem processes and functions. So far, the ecosystem service conceptualisation of wildfires has primarily considered fire as a disservice, that is, as a source of losses rather than benefits. This conceptualization emphasizes the suppression paradigm in order to avoid and/or minimize such losses (vs prevention). Fire, on the other hand, could be viewed as a beneficial regulatory service for soil nutrient regeneration, opening up space for certain plants and animals, and reducing the severity of huge wildfires. There is a trade-off between the societal (i.e., asset losses) and ecological repercussions of fire that needs to be addressed.

The guiding question for economic resilience of landscapes is: "how to achieve improved resilience levels by optimising the allocation of scarce resources?" (Basic economic problem). So far, most fire management systems have allocated (primarily public) resources in suppression, disregarding or under-budgeting preventive risk reduction interventions. This "zero-fires" approach has proven little effectiveness in large wildfires, and in extreme wildfires, highlighting the need for a paradigm change in the perspective of the future threats. "Living with wildfires" entails a social acceptance of certain fire-derived losses. Yet, what is the amount of losses that are (socially, technological, & politically) acceptable and practical is a question still to be solved for each setting. Besides, transferring suppression resources (maintaining an effective threshold) to prevention could minimize the future expenditures, hence reducing the need for additional suppression and restoration efforts. The "forest resilience bond" is an example of investment in preventative measures with frontloaded expenses and benefit that arrives later with a return for the investors.

To face the prospective large and extreme wildfires (fuelled by the energy released from the burnt landscape), there is a need to tackle two fire intensity drivers: fuel continuity (derived from landscape encroachment following agriculture abandonment), and fuel accumulation within the forest (derived from reduced forestry intervention). To reverse this entails pragmatic questions: Where treatments (including land use change) are needed? How feasible is to handle big regions when land is fragmented and how to organise that (landscape design, economies of scale)? How much treatment is necessary (intensity/frequency)? How large areas should be treated (typology of risk reduction interventions, combinations of thereof)? How much do we want to treat, combining risk reduction with other values in our landscapes?

Economic resilience might be characterized as the condition where economic actors participating within a system continue their functions before to the wildfire event. This refers to the revenue-raising function (income-generation paths through marketable products, e.g., burnt timber or scorched cork, and services, e.g., rural tourism), but also the social and ecological functions. This requires a system that minimizes the severity of the impacts, the time lapse until the recovery of the functions, ensures the availability of restoration funds to repair the losses (e.g., insurance), or the feasibility of alternative methods to exert the functions post-fire. The last point refers to e.g., the presence in the region of a company utilising burnt materials that provides an alternative revenue stream to the affected rural economy as initially planned. This reduces the impact costs in the short run, usually as one-time payment. Yet, too large (interesting) post-fire revenues also act perversely as incentive for human-induced ignitions.

Governance and risk awareness

Wildfires, particularly EWE, are inserted in a socio-environmental context, and their occurrence and impacts are expected to increase over the next decades. Integrated wildfire risk management (WFRM) approaches this complex problem, posing challenges to risk governance thinking and planning. In fact, in the event of an EWE, all policy layers managing that landscape will affect the development and the impacts of that EWE. Thus, policy coherence as a pillar given by a legal framework connecting policies planning departments, and focusing on fire resilient landscapes, is needed. Such framework may be for instance based on the risk accountability concept, with trade-off analyses and attribution of incentives or accountability for private fire resilient landscape planning or solutions that mitigate wildfire risk (e.g., guiding housing construction in very high fire risk areas and asking urban developers to reduce vulnerabilities). Insurances, wooded and non-wooded bioeconomy based, payments for ecosystem services or forest bonds, are some ideas that will likely foster fire-smart forest management (Hirsch et al., 2001) https://www.researchgate.net/publication/274546687_Fire-smart_forest_management_A_pragmatic_approach_to_sustainable_forest_management_in_fire-dominated_ecosystems, solutions (Plana et al., 2020) https://www.researchgate.net/publication/349345218_Soluciones_inteligentes_para_la_prevencion_de_incendios_forestales and policies (Vallejo-Calzada et al., 2018) https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/forest-fires-sparking-firesmart-policies-eu_en and fire-resilient territories. It may increase the interest of land management by local communities making it more profitable and attractive for investment and decreasing fuel management costs linked to direct wildfire prevention.

Only a multidimensional, co-creative, and transformative paradigm can solve the complexities of fire resilient landscape planning. For that to happen, the system of values of each landscape must be explored and defined through a planning that considers risks and climate change and adaptation. Sometimes, landscape values are protected but not their social dynamics (e.g., agricultural activities, etc.). Understanding the values in place, approaching multiple stakeholders' viewpoints, and being able to establish synergies on risk mitigation and actions on the territory that lower the hazard, exposures, and vulnerabilities are all required for fire resilient landscape planning. This involves accepting burned areas as a basic aspect of landscape dynamics and discussing the societal boundaries of suppression-centred methods (optionally including what values are to be prioritize for protection in case of a wildfire, and how to deal with temporary or permanent loss of a value). This approach will determine whether the socio-ecological system has the resources to recover from wildfires while also maintaining connection and coping capacity to follow the adaptive cycle while remaining resilient. Thus, planning tools and governance processes provide an opportunity to develop collaborative solutions including various stakeholders and responsibilities ranging from municipalities to farmers, risk managers, and urban planners, among others.

At the basis of territorial planning towards a wildfire resilient landscape, we should consider the social pillar in particular social resilience. Features such as the concept of community trauma due to wildfire and wildfire risk perception should be included while planning for restoring wildfire-affected landscapes.

Different territorial scales (including different countries) have different needs with different funding schemes. For that it is beneficial a mixed-type funding (e.g., private investment incentives and multi-fund financing such as the rural development program (RDP)) with specific funding opportunities to be applied to the most vulnerable territories from an equitable point of view. The role of public institutions could include three main topics: legislation development for wildfire risk management; financial support to fire risk mitigation actions, and auditing of both.

Wildfire risk governance through collaborative and adaptive governance can lead to actors' consensus (from forest managers to nature conservation officers, homeowners in wildland urban interface, municipalities, fire and forest services, private business, citizens, etc.) There are various narratives that can be used to understand and explain a widespread issue. This diversity enriches how we approach solutions. This can effectively solve the problems using creative ways of thinking that arise from the collaboration generated among stakeholders, based on a common understanding of each ones' role along the resilience creation process. Collaborative and adaptive governance should be inclusive and should be able to build a local community risk culture (cohesion, collective memory) across all involved. Community risk perception must be considered and included on the formula that calculates wildfire risk. Such work of understanding local community risk perception starts by knowing their culture and ancient traditions and beliefs. With a deeper understanding of fire culture and its difference between countries, communication and fire prevention may be more effective on a local, national, and international scale. The community's interest in wildfire risk management can be stimulated, e.g., by (1) being present in the field in order to build trust among the community by demonstrating the efficacy of past risk reduction actions; (2) giving them the confidence to follow up the actions; (3) conveying the idea of accountability for the actions, or lack thereof; (4) discussing among stakeholders (landowners, forest managers and politicians) the thresholds for acceptable temporary or permanent losses (i.e., the threshold for resentment and grief, according to risk perception); and (5) fostering new activities or reactivate old activities (e.g., green energy production, cork or resin extractions) to decrease fuel management costs.

The fire risk governance process is only complete if there is a good communication strategy among all involved. It is known that vulnerability to natural disasters and catastrophes decreases as people's knowledge and information increases. However, some studies point to the lack of new methods to engage with local communities in order to build a more sustainable landscape. Communicating risk can be challenging and requires a clear analysis of what needs to be communicated and how to do it. For that, a rigorous empirical assessment of the local community's risk perception is essential. The Mapping Mental Model is a technique to analyse the cognitive or personal representation of external reality, connecting the plurality of values and goals linked to different stakeholder perceptions, which can stimulate knowledge exchange, communication and learning processes (Kolkman et al., 2005). This approach creates and tests appropriate tools and techniques for effectively capturing internal and cognitive representations of the world, and it may be a suitable fit for creating a successful risk communication plan oriented for the rural population. This model can potentially give people and target audiences an understanding of the wildfire process. In addition, it will smooth the perception and acceptance of responsibility for risk management by local stakeholders/communities, as well as create favourable conditions for integrating their experience in managing other types of risks. So, governance and risk culture are complex processes since they include different mental models according territorial, educational, socio-economic contexts, etc., and the multiple dimensions of resilience may be understood as a complex system.

Nevertheless, there are always inequalities and inclusiveness gaps in landscape resilience planning. Thus, having local ambassadors (individuals and municipalities) involved throughout the planning process is a key to tackling discrimination and disadvantage (intersectionality concept, Kimberle Williams Crenshaw, 1989) among socially diverse individuals or communities, by giving voice to the least heard and increasing equality, equity, and justice within planning of fire resilience landscapes.

There is also the problem of integrating the tourist community, as they may be unfamiliar with wildfires and unaware of the risk they may face. Thus, fire ecology information and multilingual guidance for self-protection/community protection in the event of wildfires should be easily accessible to all, including those in non-fire prone areas.

To summarize, it is necessary to ensure a sustainable balance of the socio-ecological system, taking all elements into account, in order to promote, implement, and maintain fire resilient landscapes, and the centre of this sustainability will very much depend on the local communities' context, conditions, and landscape management purpose. Fire resilient landscape planning requires a transformative dimension supported by two pillars: policy coherence and social dimension. It entails a collaborative approach based on resources and risk responsibility definition, including time since it requires long-term planning. The better solutions are hybrid-type solutions where all stakeholders are given the same opportunity to be involved in, and, above all, creative thinking is promoted to tackle the issue of resilient landscapes which are multivalued landscapes. Local community enablers who understand their policy and risk culture are key for contextualizing the process and increasing its chances of success.

Resilient landscapes include resilient societies able to build and maintain fire and climate resilient territories. Since different dimensions of resilience exist and, in all, a systemic approach is needed (Fig. 25).

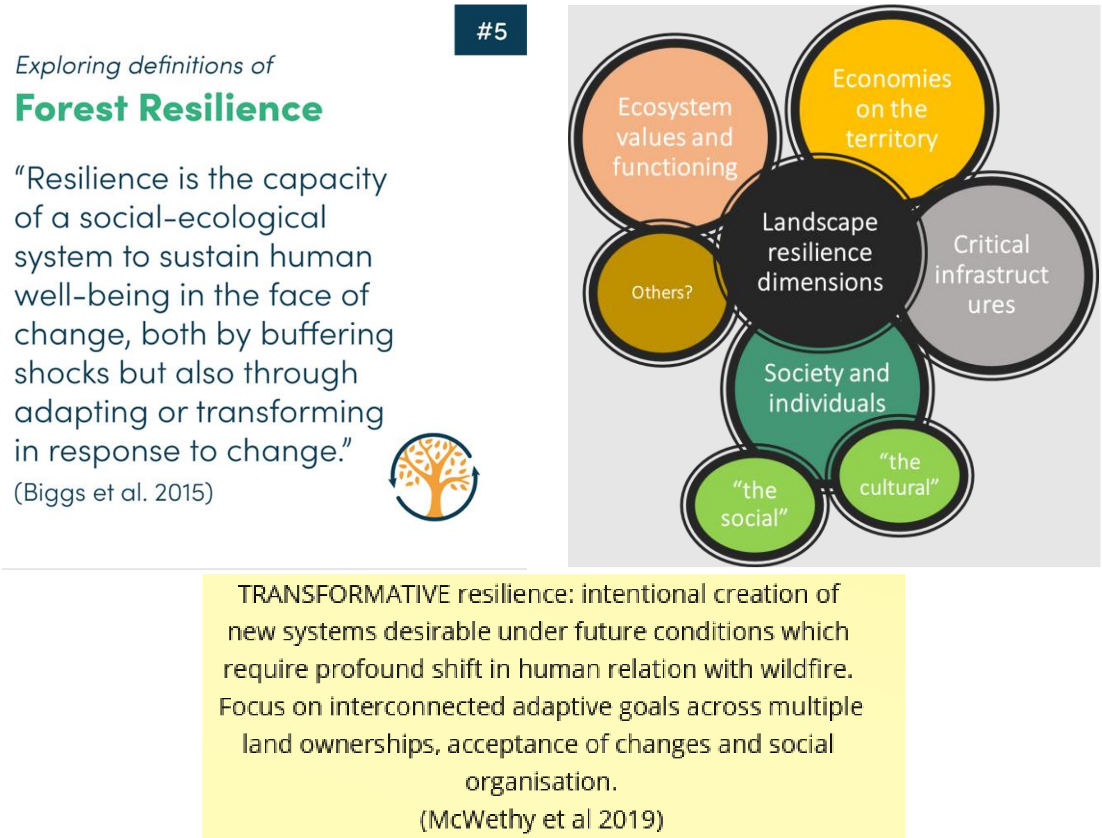

Fig. 25. Different definitions exist about forest resilience (left, from @resonate EU project) that can inspire wildfire landscape resilience and approach all its different dimensions (right) in a transformative way (bottom).

Lessons learned and guidelines

This section includes a compilation of lessons learned from the Fire Resilient Landscapes workshop for each topic. This information, in conjunction with the literature review, can be used to establish the parameters and thresholds required to assess the resilience of a specific landscape to wildfire and EWE. It can also be beneficial to discuss how to create a fire-resilient landscape.

Ecology and Landscape management

Lessons learned on "Ecology and landscape management" are based on the presentations of the following keynote speakers: Paulo Fernandes (ForestWise), Adrián Regos (CIBIO), David Meya (DACAAR), Nora Aquilué (CTFC), Lluís Coll (CTFC), and discussions with the leaders of the working groups and innovation actions.

The following are the fundamental/general principles for creating wildfire resistant and resilient landscapes:

- Decreasing the flammability of forest systems.
- Promoting open low-fuel load structures at the stand and landscape levels.
- Promoting heterogeneous landscapes (i.e., a diversity of land uses).

- Increasing the use of fuel reduction treatments. For example, it is known that managing 5–10% of the landscape in strategic places should be treated annually with prescribed burning in order to reduce wildfire size (Fernandes, 2015). Nonetheless, the 5–10% threshold is a general recommendation, so each individual landscape must be evaluated.
- Placing strategically rather than randomly management treatments oriented to reduce fire risk based on spatially explicit fire spread models. These models have the potential to optimize the leverage of a given treatment.
- Supporting grazing and browsing treatments as effective means of reducing the frequency of fuel load treatments is recommended. Thus, grazing is ideal to obtain low herb biomass and to control woody fuel load, but a regular mechanical or burning clearing is generally necessary every few years.
- The use of forest grazing with fire prevention purposes relies in the fact that farmers are maintained in the territory and cannot be understood unless it is part of a rural development strategy.
- Using wildfire scenarios to integrate ecosystem services and nature-based solutions into fire risk reduction, as well as other values we have in the landscape. Globally, the combination of different modelling approaches shows that:
    - Large agricultural and pastoral areas provide good opportunities for fire suppression.
    - Policies that combine farmland protection (i.e., initiatives aimed at reversing farmland abandonment and preserving it) with fire-smart practices create more resilient landscapes. Fire-smart practises are defined as an integrated approach primarily based on fuel treatments through which the socio-economic impacts of fire are minimized while its ecological benefits are maximized (Hirsch et al., 2001).

For creating resilient landscapes in the context of EWE, the following considerations were made:

- Surface and canopy fine fuels both living and dead, contribute most to fire spread as they dry more quickly and their moisture content changes dramatically depending on environmental conditions because they have a greater surface-to-volume ratio. Thus, fine fuels are those that are usually available and contribute most to the propagating energy flux of the main flaming front. Under extreme weather conditions, fine fuel loads greater than 10–12 t/ha result in EWE exceeding firefighting capabilities.
- Fire size may not be reduced under EWE conditions, but there are some benefits of fuel treatments in terms of fire severity that are noticeable at the local level.
- Fire can spot up to 3 km (or even much more, e.g., spotting distance of 60 km have been reported in Australia) and burn beyond expected levels (which must be considered in the context of promoting heterogeneous landscapes).

- Because fuel treatments do not appear to reduce wildfire size when burning in extreme fire conditions, fuel treatment efforts should focus on reducing damage rather than reducing the extent of EWE.
- There is great uncertainty about how the landscape might respond to EWE because current models do not capture these impacts.

Regarding post-fire restoration treatments, the following considerations should be made:

- Short-term restoration treatments should be undertaken only when there is a high risk of post-fire soil degradation. In these cases, treatments should focus on soil protection to prevent erosion, reduce runoff, and reduce flood risk.
- In the medium to long term, restoration treatments should be implemented depending on the objectives. For example, regeneration reinforcement should be required if vegetation does not recover after a fire and the risk of soil degradation increases. In this case, vegetation restoration should take the opportunity to improve ecosystem resilience to new fires by establishing fire-adapted species (e.g., resprouts). Consideration should also be given to changing the previous land use of the burned area (e.g., conversion of forest to pasture or agricultural land).

Fire as a management tool

Lessons learned on "Fire as a management tool" are based on the presentations of the following keynote speakers: Eric Rigolot (INRAE), G. Matthew Davies (SENR.OSU), Davide Ascoli (UNITO-DISAFA) and Jordi Oliveres (CFRS), and discussions with the leaders of the working groups and innovation action.

Traditional burning: the use of fire by rural communities for land and resource management purposes based on traditional knowledge.

- Traditional burning can help reduce the spread and severity of wildfires. The experience in the French Western Pyrenees is an example of how regulated traditional burning using a participatory approach can help to create fire landscapes, for example, by reviving traditional pasture burning.

Prescribed burning: the use of fire under specific environmental conditions that allow fire to be confined to a pre-determined area and achieve planned resource management objectives.

- Prescribed burning in pine forests can reduce fire behaviour for up to 10 years after treatment and fire severity for up to 3 or 8 years (depending on fire weather) (Espinosa et al., 2019).
- Reductions in wildfire area depend on fire behaviour and the extent of treatment, among others (e.g., fire regime, type and frequency of treatment, plants recovery), for which the concept of leverage can be used. In Portugal for the worst-case scenario, 5 ha of prescribed burning reduces wildfire extent by 1 ha, while in landscapes with frequent fires, 1.2 ha of prescribed burning reduces wildfire

extent by 1 ha (Davim et al., 2022). Moreover, combining prescribed burning with fire modelling assisted planning improves the leverage.

- In the context of EWE, there are few examples on the effectiveness of prescribed burning and fuel treatments in general, but there is evidence of local effects of fuel treatments on such fires. Nonetheless, during the prescribed burning session it was reiterated that efforts should focus on reducing damage rather than reducing the potential extent of EWE.

Wildland fire use: the management of wildland fires to accomplish specific pre-stated resource management objectives in predefined geographic areas outlined in Fire Management Plans.

- The current debate over wildfire use is political rather than technical or scientific.
- In the U.S., there is controversy over simultaneous "let it burn" fires with other large wildfires as resources are limited, as well as constrains linked with its social impacts and air quality.
- At the European level, in Portugal, a new law was recently passed that allows some fires to burn. It will not be translated into action on the ground but will be used to regulate the legal consequences in those cases where the authorities are not able to control the fires because of a lack of resources or uncontrollable fire behaviour.
- In Catalonia, la Vall d'Aran region is a good example of how to incorporate the use of wildland fire. A strategic plan has been adopted as requested by the stakeholders and general public of the territory. Within this program, there are management objectives that can be achieved with conventional prescribed burning, but in some specific locations the option of wildland fire use, that is a "let it burn" strategy, can also be considered. This strategic plan consists of a reference document (strategic design), a dynamic environment GIS for managers, an assessment of landscape dynamics through modelling, and a monitoring program.

Economics aspects of resilient landscapes

Lessons learned on "Economics aspects of resilient landscapes" are based on the presentations of the keynote speaker Sven Wunder (EFI) and discussions with the leaders of the working groups and innovation action.

The economic dimension of resilience has several implications on costs of the risk reduction measures, but also some direct and/or indirect benefits, which can be more or less tangible. The risk reduction interventions have potentially synergetic opportunities, as follows:

- Avoiding losses (human, material/assets, financial...) and their related reparation costs; including side effects (air pollution, community strengthening)
- Diminishing defensive costs towards optimising strategic expenditures generating economic revenues by increasing marketable production options (investments that facilitate self-maintenance)

- Leveraging extended cost-benefit ratios through optimising synergies among ecosystem services and other social and cultural benefits.
- the medium to long-term perspective in cost-benefit analyses of risk prevention measures (typically neglected).

However, there is no optimal landscape management alternative. There may be an optimal allocation of resources (chiefly, budget, human efforts) to achieve specific goals (e.g., market revenue, fire risk, erosion…). Essentially, there is no optimal risk level, consequently needing to decide which level of risk one wants to prepare the landscape for. Linked to this question is who (which agent) makes such decisions, and holds the liability for bearing the cost and implementing the risk mitigation measures? Whether it is the government, despite the fact that public resources are limited, or landowners, WUI homeowners, or anyone else. Agriculture and forest owners are harmed by some losses, but their actions also give a variety of positive externalities to third parties (e.g., ensuring landscape beauty for touristic sector). To optimize, metrics are required to generate distinct options for various purposes.

From an economic perspective, there are two approaches for fuel (i.e., vegetation) management to tackle wildfires (Wunder et al, 2021):

- Direct pathway to fire prevention, through measures explicitly targeting the fuel management: e.g., prescribed burning, thinning, shrub cleaning (mechanical)… The challenge of these measures is the maintenance of the risk reduction effects in the medium/long term, which requires some recurrent intervention and thus expenditure. This approach, yet, has been traditionally employed as it is easier to design a policy tool, having some limited effect on marketable products.
- Indirect / Bioeconomy pathway, through (re)activating value chains whose regular functioning includes activities that reduce fire risk, but their main objective is not the wildfire per se, but to produce bio-based raw materials to be sold in the market: e.g., fuel breaks through agricultural parcels, shrub control through targeted grazing, silvicultural tendering interventions, etc. These measures are more complex to effectively design, owing to the complex factors that hinder the productivity or competitiveness of the products obtained, whose approach requires actions beyond the wildfire risk management merely. Here emerges the problem of knowing how to preserve the heritage but not the dynamics creating the landscape values (difficult in targeting the measures).

The role of economic incentives:

- They are not always decisive for achieving changes in risk management by different actors: monetary inducements are effective at supporting operators being proactive (when risk reduction requires activity-enhancing measures), or at persuading land manager to introduce substitutive practices (if preliminary ones were risky, yet more profitable or known/easier).

- It won't be always about economic incentives, but also the community capacity to act. If farmers should use fire differently, it would imply a cost to them. In that case the economy acts as an incentive. But it should play at the margin. It is not always decisive, but it is a way to financially balance the situation.
- Incentives need to be designed in such a way that farmers can realistically use them – e.g., minimise advance payments, attractive enough co-financing (e.g., In Portugal, 20% of cost-sharing goat-grazing subsidies was insufficient).
- Inspiration can emerge by looking at incentive schemes and how the economic dimension is tackled in other disturbances.

In planning the preventive measures and implementation of suppression, it has been observed that:

- Wildfires themselves cause fuel discontinuities, which help in future spatial wildfire spread in the area. This hampers the task of spatial planning, as it requires constant update. When the "let it burn" approach is strategically embedded, this wildfire-led fuel reduction may constitute a low-cost approach.
- Rewilding (as reduction of fuel through promoting wild herbivorous) was mentioned as a possible tool in some specific areas yet taking into account the possible trade-offs with other land-use activities.

Governance and risk awareness

Lessons learned on "Governance and risk awareness" are based on the presentations of the following keynote speakers: Joanne Linnerooth-Bayer (IIASA), Cristina Garrett (DG Territory, Portugal), Eduard Plana and Marta Serra (CTFC), Pepa Moran (UPC), Julissa Galarza and Cathelijne Stoof (WU), Catarina Sequeira and Iryna Skulska (ISA) and discussions with the leaders of the working groups and innovation actions.

- Borrowing the knowledge and experience acquired from the management of other types of natural risks can be very useful. Hybrid solutions that recurred to nature-based solutions mixed with engineering solutions, have contributed to better options to tackle flood risk, and must be considered to tackle wildfire risk and to build more fire resilient landscapes. These solutions take time to consolidate and the more diverse initiatives and innovations in collaboration with local communities, the better the result will be (Re-naturalizing Munich's Isar River, Germany, and Co-design of a Nature Based Solutions (NBS) for landslide risk in Nocera Inferior, Italy, and Designing a flood insurance system for Hungary.
- http://www.iiasa.ac.at/Using Land Use and Land Cover (LULC) data and burned area data is the starting point to analyse the territory and understand what values should be protected, as well as its proneness for future wildfire scenarios. This evaluation and proposed resilience strategies should be objective, using transition matrixes, and the cost per unit should be discussed with the locals (both individuals and companies) in order to adapt it to the socially accepted residual disaster risk. Some examples are the plan elaborated after the Monchique wildfire

in Portugal (DGT,2022) https://www.dgterritorio.gov.pt/Programa-Reordenamento-e-Gestao-da-Paisagem-das-Serras-de-Monchique-e-Silves-PRGPSMSand the matrix linking management, loss, and permanence values in Collserola.

- Governance at the local level should give the same chance to all stakeholders to discuss and be part of the solutions, but differences in fire proneness territories should also be considered, as there are local stakeholders that are more affected. This could be addressed by creating a risk community among local stakeholders and sharing risk management responsibilities and capabilities among all of them. The most important lesson learned from the Monchique case (Portugal), is that the ambassador of the proposed must be the local authority, to ensure the adaptation of the technical studies developed to the local reality, with a participatory approach (by listening and discussing with the local community). An example of a pilot case in Spain is in *el Bruc* municipality, where, thanks to an EU project, bottom-up and top-down initiatives meet.

- The team who carries out the approach with the local stakeholders should be composed of technicians, facilitators, and communicators, and must have availability to legitimize the complex and time-consuming co-creation stakeholder process. Some examples of policy programs in course in Portugal are the "*Program a de Reordenamento e Gestão da Paisagem*" (PRGP, Landscape Replanning and Management Program), the "*Áreas Integradas de Gestão da Paisagem*" (AIGP, Landscape Management Integrated Areas Program), the "*Programa Condomínio de Aldeia*" (Village Condominium Program), and *"Programa Emparcelar para ordenar*" (Pair to Sort Program). All programs information can be found in Renature Monchique (n.d.).

- https://www.dgterritorio.gov.pt/paisagem/ptpPairing with private investors for creating more fire resilient landscapes is possible. The work developed by GEOTA NGO as the ambassador in Monchique Fire? validates the successful use of a private company funding applied to support private owners in postfire restoration (Renature Monchique, n.d.).

- Other private-public initiatives towards fire smart solutions can be founded in Lessons on Fire (n.d.)

- Raise awareness in areas with low and medium wildfire frequency due to predicted climate change and increased areas of high fire risk. This work should be carried out by linking internal and external funding, with the identification of all stakeholders to engage, as seen in Portugal, France, Spain, or the Netherlands.

- The planning process for the construction of new housing or re-building within high fire risk areas could be conditioned to risk mitigation measures, involving all public agencies in charge of spatial planning and risk management as well as local communities and homeowners.

Contribution of FIRE-RES IAs to the challenges identified

For each topic, a series of tables present the challenges to create fire resilient landscapes identified during the workshop and the corresponding innovation actions to address them.

Ecology and Landscape management

The challenges for FIRE-RES related to forest ecology and landscape management are listed in *Table 3*. With respect to the IAs of WP2, it was reiterated that landscape-level planning will be based on simulators and will therefore focus largely on large (but conventional) fires and, to a lesser extent, EWE. Due to the lack of predictive tools, EWE can only be considered as a potential event in WP2 (landscape conditions under which it occurs), but no analysis of impacts and damage can be performed. For EWE, a layer of information could be added about landscape conditions that can generate energy for an EWE (and attempts will be made to breach these conditions, and the analysed costs).

Table 3. Challenges and knowledge gaps for forest ecology and landscape management (LM) and related Innovation Actions.

Code	Challenges and gaps	FIRE-RES Innovative Action
LM1	Optimize fuel treatments (e.g., proportion of landscape treated, frequency and location of treatments (e.g., priority areas) and integrate different types of fuel treatment (e.g., prescribed burning, mechanical, grazing)) with the goal of reducing fire damage more than area burned in different biogeographic regions.	– **2.2**: Scheduling and implementing novel management practices. – **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE. – **2.7**: Landscape design strategies, using tactical planning methods. – **5.10**: Development of a Pan-European system to define management priorities to mitigate fire impact.
LM2	Establish thresholds in terms of structure/forest composition at the stand level (e.g., minimum discontinuity between vegetation layers, maximum forest canopy, maximum tones of surface fuels, maximum tones of canopy fuels) and fuel connectivity at the landscape level that may prevent wildfires and EWEs.	– **2.2**: Scheduling and implementing novel management practices. – **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE. – **2.7**: Landscape design strategies, using tactical planning methods. – **5.10**: Development of a Pan-European system to define management priorities to mitigate fire impact.
LM3	Develop landscape-scale forest management to reduce fuel connectivity and load in strategic landscape areas.	– **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE. – **2.7**: Landscape design strategies, using tactical planning methods. – **2.5**: Designing strategic networks of managed areas to improve suppression efforts against EWE.

Code	Challenges and gaps	FIRE-RES Innovative Action
		– **5.10**: Development of a Pan-European system to define management priorities to mitigate fire impact.
LM4	Establish a monitoring protocol to evaluate the effectiveness of fuel treatments.	– **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE.
LM5	Consider novel climatic events, as we cannot model future scenarios without taking into account future conditions.	– **5.10**: Development of a Pan-European system to define management priorities to mitigate fire impact.
LM6	Consider that fuel availability in a landscape changes over the course of seasons/days.	– **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE. – **2.5**: Designing strategic networks of managed areas to improve suppression efforts against EWE. – **5.10**: Development of a Pan-European system to define management priorities to mitigate fire impact.
LM7	Can EWE become predictable through active and sustained fuel management?	– **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE. – **2.7**: Landscape design strategies, using tactical planning methods. – **2.5**: Designing strategic networks of managed areas to improve suppression efforts against EWE.
LM8	Trade-offs between fuel management and ecosystem diversity (and public acceptance).	– **2.8**: Trade-off ES assessment of fire resilient landscape design
LM9	Rewilding through the promotion of large mammals to keep levels of fuel low may be an option for abandoned areas where active mechanical management or prescribed burning is not viable.	– **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE.
LM10	Bureaucratic requirements are too high. In non-productive forest systems, public funds are needed to support fuel management.	– **2.4**: Optimizing landscape configuration and fire management policies to minimize expected losses from EWE.

Fire as a management tool

Increasing the resilience and resistance of landscapes to wildfire using fire as a management tool presents the following challenges (Table 4). Most of these challenges will be addressed in IA 1.4 brief 1 and 2.

Table 4. Challenges and knowledge gaps for fire management (FM) in general, traditional burning (T), prescribed burning (PB) and wildfire use (WFU) and related innovation actions.

Code	Challenges and gaps	FIRE-RES Innovative Action
FM1	Minimizing inappropriate use of fire and maximizing its appropriate use to increase landscape resilience to wildfire.	– **1.4 brief 1**: Integrated fire management (IFM): demonstration, training and piloting activities, including new fire-prone areas. – **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal. – **5.10 brief 2**: Development of a Pan-European system to define management priorities.
FM2	In the future, acceptable windows for fire as a tool may be limited due to climate change, which will likely exacerbate the frequency and duration of high-risk and high-severity conditions.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
FM3	Need for fire management plans at forest and regional scales.	– **4.5 brief**: Report on Policy clinics
FM4	Understanding how to restore ecologically appropriate fire regimes, taking advantage of appropriate fire use and incorporating new advances in fire ecology.	– **1.4 brief 1**: IFM, demonstration, training and piloting activities, including new fire-prone areas. – **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
FM5	Evaluate interactions between fire effects and other disturbances (e.g., pathogens, drought) to identify and minimize negative interactions and maximize positive ones.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
T6	Decrease in rural communities with traditional burning knowledge.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
T7	Unsympathetic and intensive traditional burning that undermines public confidence in the validity of fire use.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
T8	Policy that increases the bureaucratic burden associated with traditional burning or outright that prohibits burning in certain situations.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal. – **4.5 brief**: Report on Policy clinics
T9	Integrate prescribed burning techniques to improve practices and outcomes without losing the knowledge and work of traditional managers.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.

Code	Challenges and gaps	FIRE-RES Innovative Action
T10	Uncertainty about the ability of traditional burning practitioners, to be adaptive in the face of climate change and to adapt their tools and techniques.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
PB11	Skills needed to be applied in prescribed burning are poor in some ecosystems (e.g., subalpine forests) and regions of Europe.	– **1.4 brief 1**: IFM, demonstration, training and piloting activities, including new fire-prone areas.
PB12	Forest composition and structures (load and arrangement) limitations.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
PB13	Nature conservation and air pollution concerns.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
PB14	Policy and regulatory limitations.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal. – **4.5 brief**: Report on Policy clinics
PB15	Cultural constrains.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
PB16	Establish a common monitoring protocol to evaluate fire impacts and the effectiveness of integrated fire management actions to inform future management decisions, including incorporating new knowledge (e.g., fire use in non-fire prone areas).	– **1.4 brief 1**: IFM, demonstration, training and piloting activities, including new fire-prone areas. – **5.10 brief 1**: Development of a Pan-European system to define management priorities.
PB17	Optimising prescribed burning treatments (e.g., proportion of landscape treated, frequency and location of treatments) and integrate different types of fuel treatment tools (e.g., prescribed, and traditional burning, mechanical tools, grazing) with the goal of reducing fire damage more than area burned, especially in the context of EWE.	– **1.4 brief 1**: IFM, demonstration, training and piloting activities, including new fire-prone areas. – **2.2**: Scheduling and implementing novel management practices. – **2.5**: Designing strategic networks of managed areas to improve suppression efforts against EWE.
PB18	Enhance peoples' understanding for reintroducing fire.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.
PB19	Update prescribed burning costs and influential factors.	– **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.

Code	Challenges and gaps	FIRE-RES Innovative Action
WFU20	Advancing in the technical, legal, and social acceptance of wildland fire use may provide opportunities to use low-intensity fires to reduce fuel load at larger scales.	– **1.4 brief 1**: Integrated fire management (IFM): demonstration, training and piloting activities, including new fire-prone areas. – **1.4 brief 2**: IFM, recommendations for sustainable fire management and best practices for new legal.

Economic aspects of resilient landscapes

Strengthening the economic resilience to wildfires presents the following challenges and gaps (Table 5). These are tackled mainly through FIRE-RES innovation actions within WP2 and WP3.

Table 5. Challenges and knowledge gaps for the economic aspects (EC) and related innovation actions.

Code	Challenges and gaps	FIRE-RES Innovative Action
EC1	Which economic incentives are effective for which behavioural change needed in wildfire risk management? Need to recognise (and eventually financially reward) land managers implementing measures entailing positive security externalities.	– **D3.1 Policy brief**: Through an in-depth review of existing fuel management economic mechanisms. – **IA3.2 brief**: Design and lessons learned from incentive mechanisms promoting spatial collaboration among agents.
EC2	Bioeconomy-based experiences to foster fuel management. Diminishing defensive costs towards optimising strategic expenditures generating economic revenues by increasing marketable production options (investments that facilitate self-maintenance).	– **IA3.1 brief (D3.2)**: Development and demonstration of a label for primary products originated from good practices that reduce fire spread and severity. – **IA2.2 brief (D3.3)**: Economic efficiency gains from new value chain solutions to stimulate the uptake of fire-preventive measures: forestry machinery innovations and stimulating tree mountain crops. – **IA4.4 brief (D4.5)**: Wildfire-safe villages include bioeconomy stimulus to buffer areas of villages.
EC3	Making insurances of wildfire potentially affected assets more attractive to insurance policy holders.	– **T3.4**: Development of parametric insurance solutions.
EC4	Leveraging extended cost-benefit ratios through optimising synergies among ecosystem services and other social and cultural benefits.	– **IA2.8 brief (D2.9)**: Trade-off assessment of ecosystem service of fire resilient landscape design'.
EC5	Optimal allocation of resources (e.g., budget, human efforts) maximizing certain objectives (e.g., market revenue, fire risk, erosion).	– **IA2.4 brief (D2.5)**: Optimising landscape configuration and fire management policies to minimize expected losses from EWE.
EC6	Need to identify the acceptable level of losses and to decide which level of	– **IA4.1 brief (D4.2)**: Fire forums as territorial discussion platform to discuss emergency

	risk one wants to prepare the landscape for, as well as clarifying liabilities.	scenarios and consequently reformulate liabilities in fire preparedness and response.

Governance and risk awareness

The following challenges have been identified from the governance and risk awareness perspective (Table 6).

Table 6. Challenges and knowledge gaps for governance and risk awareness (GR) and related innovation actions.

Code	Challenges and gaps	FIRE-RES Innovative Action
GR1	Make local communities accountable for risk managing.	– **1.4 brief 2**: Through Gamified risk awareness rapid appraisal, and Fire dilemma puzzle.
GR2	Rapid risk awareness assessment - explore the role of human behaviour in shaping individual and collective livelihood resilience to collective shocks.	– **1.4 brief 1**: Integrated fire management (IFM): demonstration, training and piloting activities, including new fire-prone areas.
GR3	Integrate traditional burnings and/or prescribing burnings (cultural knowledge and giving local communities a role).	– **1.4 brief 1**: Integrated fire management (IFM): demonstration, training and piloting activities, including new fire-prone areas. – **2.2**: More efficient biomass reduction. – **2.4**: Test different management policies. – **2.5**: Designing strategic networks of managed areas to improve suppression efforts against EWE. – **4.5**: Report on Policy clinics. – **5.10**: Development of a Pan-European system to define management priorities to mitigate fire impact.
GR4	Need for post-fire restoration treatments to create sustainable landscapes.	– **1.5**: Post-fire restoration. – **2.6**: Spatial multi-criteria decision analysis for restoration actions.
GR5	Improve landscape management to create fire resilient landscapes (pre-plan recovery capacity, to adapt landscape to the potential impact of EWE).	– **2.2**: Fuel management cost reduction. – **2.4**: Test of different management policies. – **2.7**: Optimization landscape-level forest management plans. – **4.6**: Fire-smart risk governance. – **5.3**: Improving the description of the vegetation of forest ecosystems. – **5.10**: Development of a Pan-European system to define management priorities to mitigate fire impact.
GR6	Increase understanding about the importance of ecosystem services for reducing fire risk.	– **2.8**: Development of novel regulatory ecosystem services framework and its integration in fire and forest management planning.

GR7	Develop and/or improve economic incentives and financing tools and schemes for landscape wildfire resilience.	– **3.2**: Developing and testing contingent economic compensation schemes. – **3.1**: Seminar with wineries on best practices. – **3.3**: Risk transfer solution. – **2.2**: Fuel management cost reduction.
GR8	Develop bioeconomy within WFRM.	
GR9	Recognize and deal with stakeholders' diversity (perceptions, values, and goals for the landscape), and develop an effective risk communication strategy to reduce accidental fire ignitions.	– **4.2**: Through mapping mental model approach.
GR10	Understand community risk perception and risk culture and create tools to make knowledge available for new rural generations and other stakeholders.	– **4.3**: Web-based educational platform.
GR11	Introduce and integrate knowledge and experience in the management of other type of risks.	
GR12	To have available clear guidelines for self-protection, individual resilience, and specific response in case of a wildfire.	– **4.4**: Fire-safe villages. – **4.6**: Fire-smart risk governance and planning legal frame and tools.
GR13	Promote a policy coherence framework: Bottom-up & top-down initiatives meet.	– **4.5**: Report on policy clinics. – **4.6**: Fire-smart risk governance and planning legal frame and tools.
GR14	Assess inequalities and inclusiveness gaps in landscape resilience planning.	
GR15	Support wildfire risk integration into urban and spatial planning.	

Fire resilient landscape in FIRE-RES

The concept of resilience has evolved significantly over the past few years, resulting in a variety of terminologies and approaches: from recovery to its initial state, the traditional approach; to adapt or transform to a new state according to ongoing climate change. Following earlier definitions of resilience, FIRE-RES aims to establish an operational tool that considers multiple dimensions (e.g., environmental, social, and economic) to provide a more precise and accurate assessment of fire resilient landscapes, since most approaches focus solely on one dimension. This tool will analyse fire-resilient landscapes on multiple dimensions using a variety of quantitative and qualitative measures. It will allow identification of strengths and priorities in a given landscape to be resilient to EWE and show where classic, adaptive, or transformative resilience should be promoted.

There are examples of the use of multi criteria analysis to consider different aspects of resilience (e.g., Pukkala 2021, 2022). Qualitative and quantitative data related to the different dimensions considered may be combined by using utility functions.

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Annexes

Extreme wildfire event (EWE) definition process

Since the objective of this deliverable is to establish the general framework, the specific scopes of the definition will be found throughout the project. The elements that make up the definition are the following:

EWE definition focusing on fire behaviour and operational predictability (uncertainty).

An Extreme Wildfire Event is a fire that shows extreme behaviour and leads to high level of unpredictability:

Fire behaviour: The definition should have ***thresholds*** based on **management capacities**. Some of the key variables that can define an EWE are growth rate vs rate of spread (ROS), although the door is open to use other criteria such as size, energy released, or others.

Operational predictability: Predictability is reflected by fire models, which can be quantified in probabilistic forecasts and reflected by the atmospheric plume level. So, this predictability is not only based on the fire but also on the atmosphere.

Outliers and anomalies in historical data: This means that they should have a context depending on space and time. So that could be expressed as ***percentiles***.

Complementary, in this project we also consider wildfire disasters. These are fires that are outside a range of historical data in one of its descriptors (size, ROS, fatalities, etc.) and/or have a big impact on ecosystems and societies. Usually, these fires are more context dependent.

An EWE might be a wildfire disaster or not, but they are usually associated one to each other. Before arriving at the level of EWE according to a series of criteria, it could be proposed to use a scale for escalating behaviour, in which the final level is the EWE (similar to hurricanes).

Process to arrive at a definition

Introduction

The need to have an EWE definition within the project

At the start of this project, it was realized that when talking about extreme wildfire events (EWE), there were different interpretations of the concept due to different perspectives. This highlighted the need to address the concept in order to arrive at a definition to work within the FIRE-RES project. What is extreme in one region may not be extreme in another, and this can be linked with the response capacity, the knowledge acquired, the number of times the organizations have faced the phenomenon, etc. For all these reasons, it was decided to approach the concept within the framework of the project from a practical point of view, with the aim to create a frame of reference that allows the partners to have a shared vision of the phenomenon we are facing. In this way the project can specifically address these EWEs and focus innovations on them. It is the EWE that poses important challenges for which there are currently not many answers.

We found out that there are some elements that contribute to confusion about the term EWE within the project:

1. There are some characteristics that can make a concept diffuse and contribute to the linguistic uncertainty. This includes:
   - Vagueness: the inability of a concept to categorize borderline cases
   - Ambiguity: terms having multiple meanings
   - Context dependency: a lack of context that would allow meaning to be understood
   - Indeterminacy: unforeseen ambiguity arising through changes in meaning over time
2. An unstandardized use of the concept could contribute to mismatches between perceptions and reality of trends in fire activity. For example, the study of Doerr & Santin (2016) contrasts the widespread perception of increasing fire activity with empirical data that demonstrates an overall decrease in fire at both global and some regional scales.

WS1 of the project included a section to discuss the definition of EWE in order to facilitate to share the same vision of the phenomenon when for example agreements are made about procedures and capabilities needed to face EWE, to promote knowledge on the drivers of extreme behaviour and why organizations may collapse in front of EWE, to include regional variabilities and context dependence, and, in general, for actions within the project.

The following sections show the structure followed during WS1. The MIRO BOARD application was used to conduct the discussion with the aim of generating a brainstorming session to gather all the perspectives that the definition should contemplate within the project.

This annex includes the comments and elements of discussion that emerged during the session to find a definition of EWE during workshop 1. All the information has been compiled to give a broad overview of the issues and content that emerged and how they emerged for reference.

Some questions about approaching a definition

During the discussion, some questions about the definition raised up and are worth considering:

- What is our need regarding the definition of EWE?

- Is it important for us to know at the response phase that it is an EWE, or is it enough to know it afterwards? Considering one or the other option of this question makes the difference between unpredictable and unexplainable.
- If the emergency managers know at the starting of the fire that it will be an EWE, will they modify the way of managing it? Will they modify the action they will lead? This appears to be a big question because it marks the difference about focusing on unexplainable and not on unpredictable.
- If it is unpredictable, what will emergency managers say to the population as they still do not know what will happen?

Base definitions included in the FIRE-RES grant agreement

The definition included in the Grant Agreement of the project is based on

1. Tedim et al, 2018: EWE is defined as: *a pyroconvective phenomenon overwhelming capacity of control (fireline intensity currently assumed ≥ 10,000 kWm−1; rate of spread >50 m/min), exhibiting spotting distance > 1 km, and erratic and unpredictable fire behaviour and spread. It represents a heightened threat to crews, population, assets, and natural values, and likely causes relevant negative socio-economic and environmental impacts. (*https://www.mdpi.com/2571-6255/1/1/9)
2. Collapse of the capacity of emergency organizations to extinguish a wildfire (FIRE-RES GA).
3. Those events that exceed the general capacity of suppression as dictated by technological and physical constraints (Tedim et al, 2018).

During WS1 it was taken into account that within the project, it might be possible that some areas or fields may consider that the definition does not address the concepts and areas they are working on or the elements they often use as a basis or the implications in their fields.

Expectations from definitions

From the project's point of view, the definition generates the following expectations:

1. Thresholds on fire behaviour based on management capacities
2. Historical anomalies. Context dependent.
3. Predictability anomalies.
4. Other thematic needs (security, forest management, social awareness...)
5. Proxies based on available homogeneous data

In search of the definitive definition

Large fires, with large impacts (on human lives, on ecosystems), with large pyroconvective behaviour have always existed, and both firefighters and scientists have always tried to parametrize and define those concepts.

The definition of EWE has changed over time, both on the ***thresholds*** based on **management capacities** that may change some day and on the **operational predictability**.

When something new has been happening, efforts have been made to find a new word that includes those things that we are able to observe and detect at the time. This does not mean that they have not happened before, but that at that moment we are able to give them a name. Moreover, what is new is what we are most concerned about and what we want to name. In bibliography the evolution made by concepts (concepts trying to define large and extreme fires) has been the next:

- 1936 they began to talk about wildfire disasters after some fires with lots of casualties.
- 1954 they talked about tragedy fires but also about blow-up fires with this concept of sudden change to the worst.
- 1963 mass fires as big crown fires crossing landscapes with really high intensity.
- 1994 mega fires, where the only new concept was the change linked to ecosystems and the changes approached from an ecosystem scale.
- 2018 EWE

There are more words related to urban conflagrations and many other concepts. But all of them have always been trying to capture the problem and to capture what is worrying society at that moment. We always tray to capture all the information in the last concept and then we need a new concept just to focus again, so that is a continuous process.

Therefore, it is sometimes preferable to use different concepts rather than having one all-inclusive concept for ease of use and to avoid making it so general that it is not easy to apply. In the case of the EWE, it was proposed to distinguish those attributes that refer specifically to EWE linked to the process or behaviour of the phenomena from those that pertain to natural disasters and are linked to the impacts.

During the workshop, different aspects were discussed in order to arrive at these different definitions, taking into account certain differences:

Differences considering behaviour or other items:

A. Definition '*sensu strictu*' based on fire behaviour and predictability, including temporal distribution, fire distribution, fire characteristics, showing the emerging pattern.

B. Definition '*sensu latu*' based on causes, the drivers, the impacts, economy, the atmosphere, the uncertainty that comes from the process, the uncertainty that comes from all the data, etc.

Difference considering the challenges:

A. Definition considering global challenges: this definition is based on what the wildfire community is facing globally, the global challenge (Chile, in Portugal 2017, in Australia 2019-2020) linked to the extreme fire behaviour.

B. Definition considering regional challenges: the definition is based on the regional perspective in the sense that some fires might be new in an area but not in other areas and then the challenge in those areas is not creating this new knowledge but the transfer of knowledge. This definition is linked to the extreme impacts.

Difference of EWE considering the impacts:

- **Extreme emergency management**: what is extreme is what the fire threatens and requires an operative response.
- **Ecological fire disaster event**: which considers that the event has had a very huge impact in terms of ecological impacts.

This difference agrees with Tedim et al, 2018: "*EWEs should be operationally differentiated from disasters, because an EWE does not necessarily become a disaster. A wildfire disaster can be the consequence of an EWE, but it can also be the consequence of a controllable phenomenon (a normal wildfire event) because of inadequate management of control actions (e.g., lack of resources, lack of coordination between emergency teams, wrong instructions, wrong evaluation of situations), lack of preparedness by concerned communities, poor land management that has not adequately modified fuel* continuity (**Figure 2**)*. Conversely, individual large fires simultaneously burning that compete for resources, decrease the likelihood of early fire control and thus increase the chances that any given event will become an EWE or even a disaster* [49]."

The use of statistics

Generalized extreme value distribution can only be used for drivers that can be quantified. As the definition for the FIRE-RES project goes far beyond quantitative values, the statistically based on the mathematical definition of what it is extreme can only address a part of the definition.

The study to the distributions in fire size, in fire speed, etc. can shed some light. For the values and thresholds considered in previous sections, an analysis of what is extreme can be made but the data between regions varies considerably. Statistical study on some values may be of interest. Extreme values of statistical distributions could be studied to obtain certain thresholds and define as extreme the one that exceeds an agreed threshold by X.

Some parameters that could be measured with this aim could be the next:

- **Rate of spread** because it is easy to measure on-field, with satellite data, with the drones, etc.
- **Growth rate** as hectares burned per hour, which is somehow the rate of spread but not linearly, but including the extent.

A 2-dimensional description of extreme (rate of spread vs growth rate, or growth or rate vs burned area) could also be used.

Considering the fire event, some fires have long duration. During a forest fire, there can be different extreme moments. This raises the question of whether we should consider each extreme fire as an event in itself or separate the different extreme events within the same fire and discard those that are not extreme. **Extreme wildfire events can have only one hour of extreme behaviour** and the rest is normal. Some responders use the concept of burning period to differentiate between different moments along the wildfires.

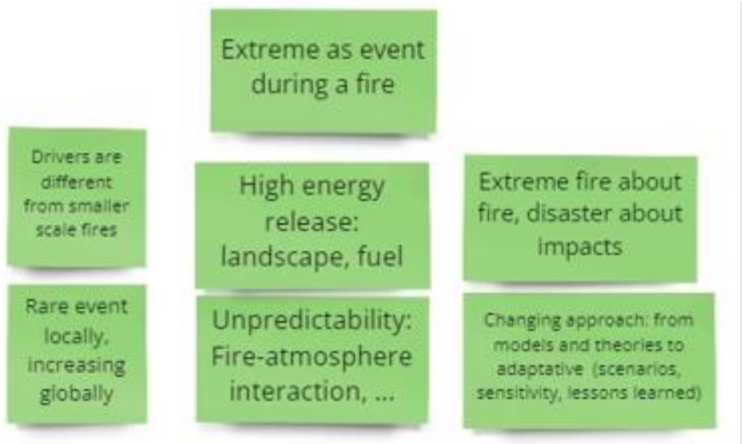
Other quantitative values linked to fuel models, forest structure, vegetation moisture, etc., as one of the drivers of the EWE, could also be measured and analysed.

But in the research field there is not an agreement of what an extreme event is. In addition, the amount of data from current EWE is sparse so that robust conclusions may not be possible at the moment. For this reason, it is interesting to approach the definition from other fields than statistics or at least not to base the definition only on this aspect.

Elements of the definition appeared in the WS1 discussions

EWE drivers' discussion

The following characteristics emerged during the driver discussion:



- Unpredictability: fire-atmosphere interaction ...
- Rare event locally, increasing globally.
- High energy release: landscape, fuel.
- Extreme fire refers to the wildfire, while disaster refers to the impacts.
- Extreme considered as an event during the whole duration of a wildfire.
- Drivers are different from smaller scale fires.

– Changing approach: from models and theories to adaptive (scenarios, sensitivity, lessons learned).

EWEs are a rare event locally but are increasing at a global scale. This has a huge impact, and it is very difficult to gather both knowledge, science, and experience unless a major effort is made in focusing on them. Those are not low intensity fires but fires with a large amount of energy release due to landscape and fuel processes behind that.

EWEs are highly unpredictable, and this seems to be strongly linked to the fire-atmosphere interaction that produces pyroconvective type fire behaviour. This is non-linear, it has high complexity, and it has huge scale (100 km winds being affected of fire environment).

There is a difference between EWE and disasters concepts. It is proposed to address EWE on the basis of how rare it is and considering that their drivers are not the same as in smaller scale fires. The way that the small fires interact is different than those of larger scale. So, it is not necessary to put more efforts to look for information on drivers at small scale, but to focus on the way they interact to form new patterns. So, to approach the EWE **rareness and the scalability**, we cannot focus on gathering a lot of information to build models, but on taking a more adaptive approach through scenarios, sensitivity and lessons learned. On the other hand, we have the disasters that are more focused on **impacts**.

Emergency management discussion

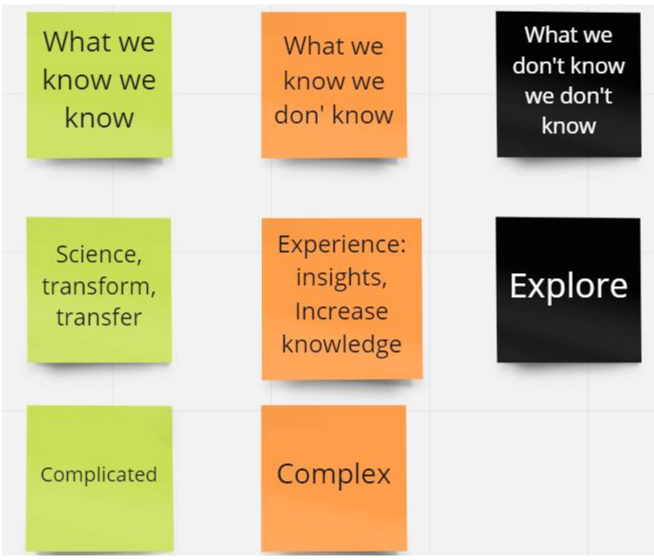
– Unpredictability
– Collapse of decision-making
– Collapse of credibility
– Internal and external communication
– Exceeding management capacity
– Tactical, organizational challenges: known, complicated
– Interoperability, fire analysis, command system, logistics

From an emergency management point of view there are two key elements:

1. **Exceeding management capacity**. This is part of the definition already included in the GA. The exceeding of the management capacity causes challenges, tactical challenges, organizational challenges, that are not easy to solve and require **very long time to adapt to, it requires years and changes in organizational level, society level, interagency, all on a very large scale**. Emergency managers have been responding to these fires that are exceeding the capacity of management through a long time. Southern communities of Europe seem to be more used to these situations than the Northern ones. To meet these challenges, they have been working in interoperability, focusing fire analysis on rare events, accumulating knowledge and experience on few people that try to understand these large fires or more complex fires, working on incident command systems (IC), on coordination between agencies, on logistics, etc.
2. **Unpredictability**: described in 2 ways.
   a) **Collapse of decision-making**: there's no anticipation, command and control collapses, etc. and at the end the response system is not there when the things happen, and the firefighters are in an environment where their decisions are not safe because their decisions need a certain amount of predictability to be safe.
   b) **Collapse of credibility**: this is a huge issue for emergency services.

Uncertainty: predictability and explanation

Uncertainty (in fire management decision making) is a situation in which wildfire knowledge is too limited or unfocused to allow making good decisions for efficient and safe operations [Castellnou, et al.; 2019].



One way of measuring the unpredictability and uncertainty is having information on "what we know we know", "what we know we don't know", "what we don't know we don't' know" and that can give us some information about what is extreme.

The following points describe what we can do to try to solve each scope of the problem:

- "**What we know that we know**": put more science, make the way to transform things, and transfer knowledge.
- "**What we know that we don't know**": to gain more experience, to put insights and to increase knowledge.
- "**What we don't know that we don't' know**": being aware that there are a lot of issues that we don't know we don't know, to try to reduce the number of things that we don't know we don't know and explore.

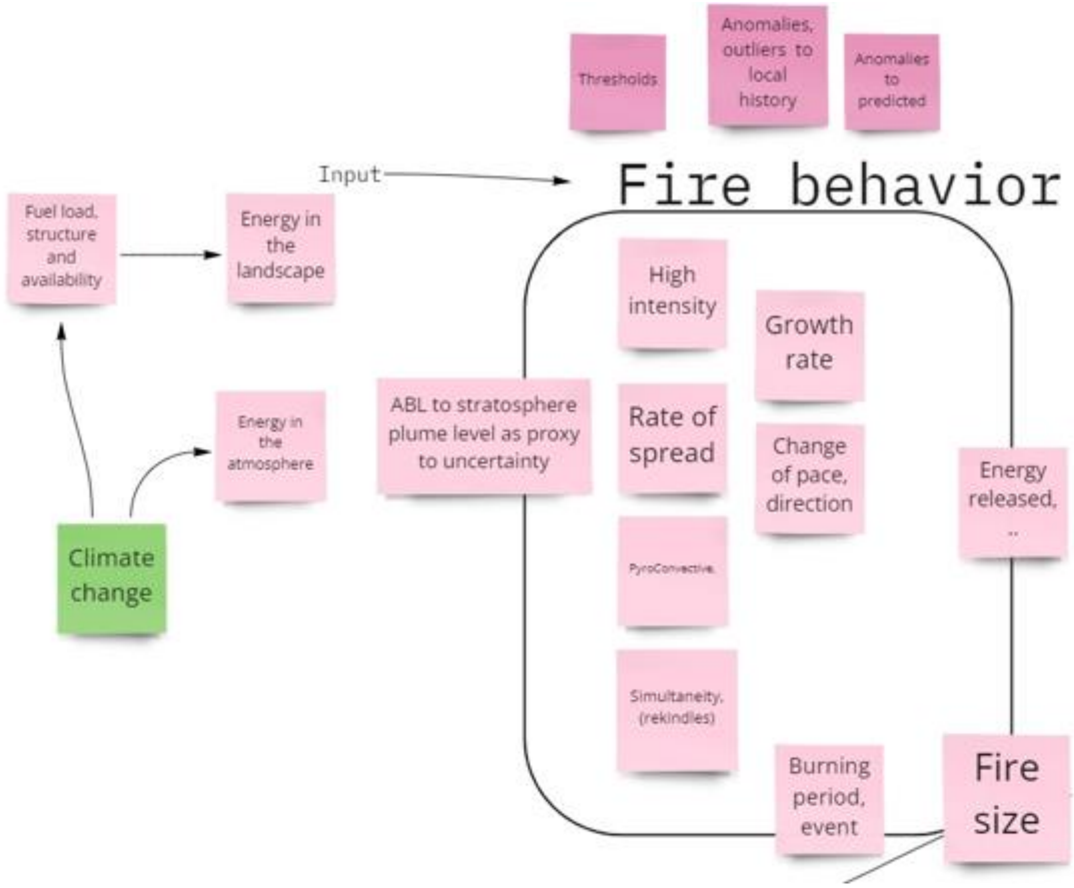
The **EWEs are complex** phenomena. Huge fires are different from Extreme wildfires. Huge fires are complicated phenomena, but the emergency managers know how they work and how to predict them. But EWEs are such events that even if we consider them not totally unpredictable, they can be **unexplainable because our current knowledge is limited**.

Detecting sources of uncertainty in fire management scenarios should unquestionably be part of the decision-making process but bringing values such as future landscape and resilience into the decision-making equation is equally important [Castellnou, et al.; 2019].

Creating tools that can help us to detect sources of uncertainty and methodologies for dealing with uncertainty can help facilitate taking the initiative in such situations.

The difference between unexplainable and unpredictable is very relevant, because it is linked to **liabilities** because if you can explain and predict something, decisions should be made accordingly. Liabilities have been driving very important changes on decision-making from emergency managers, so liabilities can be a very important part of the social part of the definition. It is important to notice that with our current knowledge maybe **something can be explained after it has happened but not necessarily before**, and this is a very relevant point when addressing responsibilities on the actions and decisions taken, both during, before and after the emergency, as they condition the scenario for its resolution.

Fire behaviour drivers



EWEs have high intensity and high rate of spread (ROS) and this can also be related with growth rate and energy released. But EWE can also be described according to pyroconvective activity and energy released also taking into account the simultaneity of fires. Climate change is affecting both, energy in the landscape and energy in the atmosphere.

So, the inputs for having some fire behaviours are:

a) **Energy in the landscape**: which has to do with the fuel load, fuel structure and its availability.

b) **Energy in the atmosphere**: which has to do with temperature and humidity patterns.

These items can be described as variables to be measured to look for the threshold of EWE development. These can also be described as challenges for an organization because it is an anomaly from what they are used to. But for any society, they are also an anomaly from what they are used to in their local history. **This is what is driving innovation and learning in organizations and in systems**, and we can also describe them as an anomaly to what is predicted. Therefore, there are:

a) Thresholds

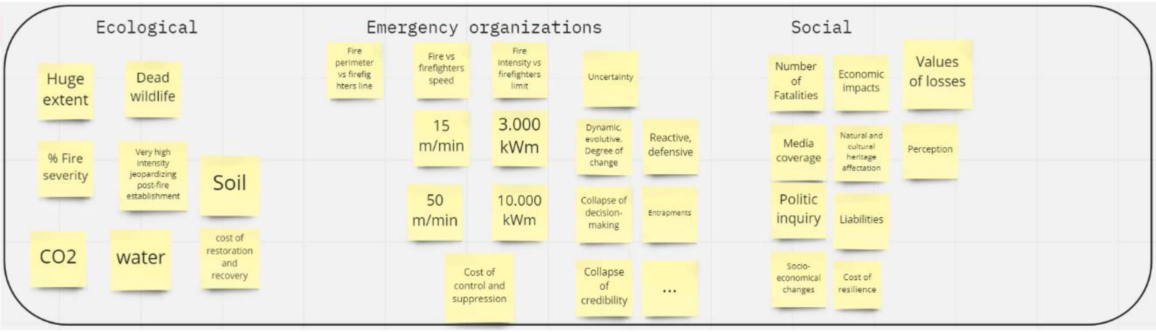
b) Anomalies, outliers from local history

c) Anomalies from predicted wildfire behaviours

Fire size

Fire size has historically been a way to describe mega-fires or large wildfires. It is a result of fire behaviour, and it is also linked with impacts. It has been really useful in the past but nowadays it is necessary to have more information than hectares burned to know if a fire has been extreme or not. It is necessary to have more information about the behaviour, about the response, etc. Therefore, fire size can be useful, but it requires to be added to other drivers, concepts, and information.

Impacts



Three main groups of impacts were considered:

– Ecological impacts
– Emergency organizations impacts
– Social impacts

- **Ecological impacts**

Ecological impacts include:

– **The extent of the fire**. The value can be useful to assess if the analysed fire is larger than the historical natural variability of its system and also if it threatens a whole biome or a whole distribution of species. This can be a way to see if the fire is extreme in terms of the extension of the fire. For example, in 2019–2020 Australian Black Summer fires there were habitats of certain species that burned such a high percentage that it put their viability to persist at risk (about the 90% of their habitat). In 2021, there was a fire in Sierra Bermeja (Spain) that threatened to affect the Pinsapar (Abies pinsapo) a kind of forest that is relict.
– **Dead wildlife**. Black Summer Fires in Australia reported more than one thousand millions of animal's death.
– **Severity** in terms of the effect on vegetation. This can be assessed by comparing the area burned in a fire with high severity with the past ones. For example, if there are fires that burn 25% of the area with high severity, and there is a fire with 90% of the area burned with high severity, the latter could be considered an EWE (if decided that this is the appropriate threshold) in terms of ecological impacts. But not only the amount of area burned with high severity is important, but also how this severity has

been in a single point, jeopardizing the capability of the species to establish again, affecting soils, affecting the seedbank, etc.

- Other impacts to consider are the amount of **carbon emissions, soil degradation** or the impacts on **water systems**.

- **Impacts on emergency organizations**

Emergency organizations often have to deal with situations where they must address fire behaviour vs their capacity. For example: dealing with how long the perimeter is and how much the lines of containment must be, how fast is the fire spread and how fast firefighters are building lines to contain them, how intense is the fire and which is the threshold of intensity firefighters can work with without suffering burns, considering where do they have opportunities, and what can be predicted.

There are some general variables and thresholds to be considered. These values need to be taken as an approximation, because they depend on different working conditions (accessibility, fire suppression technique, etc.), but they can serve as a guideline:

- Velocity: **15m/min** (1km/h) and **50m/min** (Tedim et al, 2018 value).
- Fire intensity: we go from **3.000 kW·m to 10.000 kW·m**

One of the key issues of uncertainty is the speed of change. It is not only a matter of how fast a fire is, but also how is the acceleration. Following the same idea of the blow-up fires, important are the degree of change in direction, the degree of change in speed that can surprise the system, the collapse of decision-making and the collapse of credibility. They are linked to a very reactive and defensive mode of operation in emergency management systems which causes that the initiative is on the side of the fire, not on the emergency management system. Other impacts are entrapments or impact on civilians that are unprotected during the emergency.

- **Social and economic impacts**

Social impacts can be measured based on the following elements to define what it is extreme. The **number of fatalities** is always related to what we define as an extreme wildfire event.

Economic impacts can be measured in terms of the infrastructures and forest resources that were affected or in terms of the economic value that is in the landscape behind the burned hectares alone. The **cost of suppression (a)** can be an indicator of what it is extreme, and the **value of losses regarding recovery costs (b)**, and the assessment of whether they are feasible or not from a sustainable perspective. So, there are two aspects to defining what an EWE is from an economic perspective:

a) When the event itself is running:

   - **The costs of the fire control and suppression** can be considered. If there is an average cost per hectare for a wildfire, above this threshold it may be considered as a disaster because it is above normal and it has a substantial impact on society.

- When the event is not running, after the event:

  Fatalities (human lives), maybe a price cannot be defined strictly but even the insurance companies use a price value for human lives; in terms of assets, and also in ecosystem services. So, all these losses can have a value, sometimes they are market prices, sometimes they are social values that we can capture.

  They may have a **recovery period**. It may be that the impact is so high that so huge amount of resources is needed that they never come back to the same status; but for those that can recover we have to take into account also the **recovery cost**. An EWE could be something, that it is very costly to come back to the previous status or to a status that is desirable for society. So maybe for these calculations, taking into account the climate change conditions, it is not possible to consider the previous situation because it is not possible to return to the previous situation. But on the contrary it might be considered to recover to a state that will help to be more resilient into the future.

Perception

Perception can be measured by how society is feeling about the fire, i.e. whether it is extreme or not. This measurement can be linked with the definition of '*extreme*' and is directly related with the historical variability of the fires. Therefore, if there is a very large fire compared to what the local community has witnessed before, this jump in behaviour, in collapse, or in burned area can be socially perceived as an extreme wildfire event from a local perspective.

The media coverage has impact not only in communication but also on how the society perceives the impact. Fires in remote locations tend to have less media impact than those in more densely populated and tourist areas, even if they are larger in size or have a more severe impact. In addition, there are sometimes political enquiries that follow the media storm, making this a very political issue.

Natural and cultural heritage

The impact on the **natural and cultural heritage** can influence whether a fire is considered extreme or not. For example, fires affecting iconic areas with a lot of symbolism, cultural items, or natural items can be considered more extreme than other fires affecting marginal rural areas with less population or with less values in the landscape. So, this can be a way of measuring whether this fire can be seen as extreme or not.

Cautions to be considered

Baselines, anomalies & predictability

There are some important cautions to consider when approaching a definition.

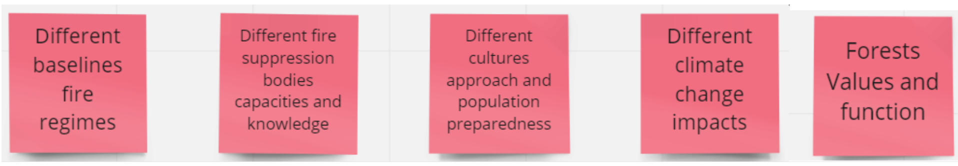
It is important to **be careful with baselines when defining whether something is extreme or not**. To define something as extreme it is important to use historical data, but it is also important to distinguish between having 20 years or 100 years of data. The definition of extreme may be a definition distorted by the amount of data considered. In addition, information on extreme events may be scarce, even considering all available information, due to the difficulty of data collection or other reasons. So, caution is needed when considering baselines.

Caution must be exercised **with local anomalies to define something extreme**. It may be advisable to define extreme as local anomalies, because what is extreme in one area might not be extreme in another area.

Caution is needed when using **predictability anomalies to define something extreme**. When focusing on predictability it must be defined what is predictable, and that is also difficult. When dealing with predictability, one has to define the limits of predictability, which is a difficult task in itself.

Regional Variability

- Different baselines of fire regimes.
- Different fire suppression bodies, capacities, and knowledge.
- Different cultural approaches and population preparedness.
- Different climate change impacts.
- Different functions of the forests in different regions.



What is extreme for some may not be extreme for others, so it is important to consider the regional variability.

The regional variability considers that the fire regimes are different. Fire regimes regarding these socio-ecological activities are not the same in the southern Europe as in the northern Europe. Therefore, there are **different baselines of fire regimes**, different **fire suppression bodies, capacities, and knowledge** because different organizations are used to these different fire regimes, **different cultural approach**, which is also linked to the **population preparedness**.

The **climate change impacts may not be the same across the different European regions** because some regions are closer to an arid area and other regions are closer to the border area more prone to be affected by the climate change.

The forests have different functions depending on the region. The **main values and functions** of a forest can be production, soil protection, water provision, etc. All functions are important in general terms but depending on the regions or areas, at the European scale level, some of these functions can be more important than others. The **main functions associated to forests**, this is forest **values and functions**, sometimes can have an economic value (timber, non-timber products, etc.) so both are worth it to consider from a regional perspective.

The **stakeholders and the people who are making decisions** are different along the regions. This is linked with the forest values and change across regions and realities. For example, there are different amounts of private and public forests in different regions. This is important in planning because it is linked with agreements and plan approvals.

Recovery from impacts

Considering climate change, maybe there will be some processes that cannot be recovered, even society will not recover, if there will be a real extreme and a municipality or town disappears due to an EWE. So, when taking into account the impacts and the points to return to, it would be interesting to take this into account.

For example, considering forests in different regions with the same severity and with the same burned area, they might not have the same capability to recover according to the previously existing species. And it has also to do with adaptability.

Scopes for the proposal

Predictability is a mix between experts' knowledge and what models and indicators are providing, but this expert's knowledge can be also related to an axis between fire behaviour and interaction with the atmosphere.

Predictability & energy release (Akli Benhali)

The proposal is to define extreme based on predictability and energy release.

The energy release integrates the rate of spread, the fire size, the intensity, etc., so it is a measure that can aggregate these components of fire behaviour. Therefore, the **extreme phenomena could be considered to exist when the predictability is low, and the energy release is very high**.

The definition should be homogeneous for the globe, and a certain type of forest fire should not be labelled as an extreme wildfire just because some local area does not have the capacity or the knowledge to deal with it and it supposes a challenge for that local area.

Uncertainty and data on the coupling between the atmosphere and the surface (Marc Castellnou)

The levels of predictability that could be considered are the following:

- The highest predictability exists when the fire is only interacting with the surface boundary layer, which implies that there are parameters that we know how to measure.
- The moderate predictability exists when fire is creating part of its environment because it is gaining to the mixing layer, causing updraft and in draft.

The low predictability exists when the fire gets into the free troposphere. These three levels mark the type of data we can obtain considering the atmosphere-fire coupling:

- Data we can and know how to measure today (highest predictability) and we are used to get them.
- Data that we can observe (moderate predictability) from indirect calculations, on-field observations, etc.
- Data that we cannot have at all (low predictability).

This is how we measure predictability in terms of things that we can objectively observe, or things that we can barely understand, and distinguish both from what we cannot observe at all.

Sources of uncertainty in planning (Jose Ramón González)

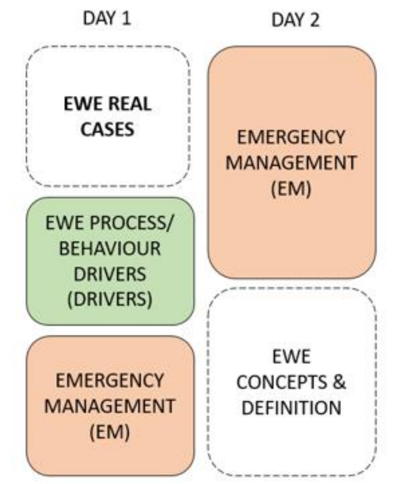
Different sources of uncertainty can be considered from planning perspective:

- Low uncertainty: It is the level that considers the impact on the forest plan that will be developed. This implies considering that if we manage the forest, we will cause certain impact.
- Moderate uncertainty: This level refers to those processes about which we have some knowledge.
- High uncertainty: This level refers to **how the unknown will be converted into uncertainty, so it could be included it into the forest plan**.

Workshop methodologies

Workshop 1

Tables of discussion



The workshop 1 was divided into 2 parts with the general topics described next:

Section 1: DRIVERS + EM + IFM

- EWE process/behaviour drivers
- Emergency and fire management

Section 2: EWE CONCEPT

An important point of the workshops was to address the concept of EWE, but it was not done so from the outset because it was considered important to first observe the phenomenon, the situations that have occurred, to listen to the experts. During the first day, EWE was discussed, but it was not until the second day that the concept itself was addressed.

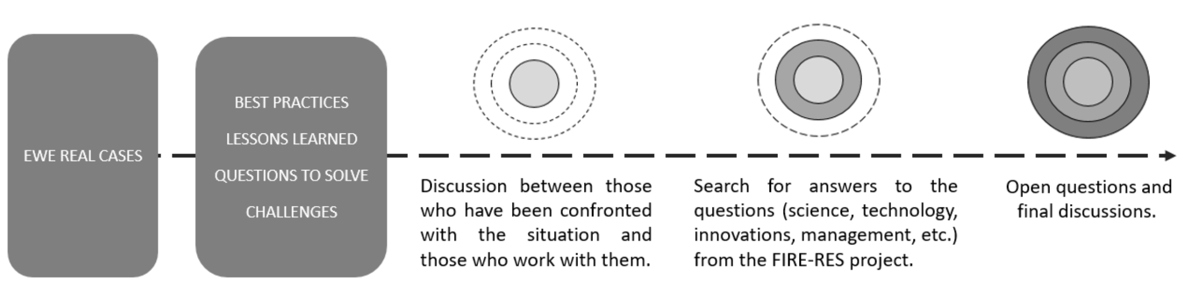
Two different methodologies were followed, one for each section.

Methodology section 1 (CIRCLES)

For the first section, we used a methodology that, starting from an initial group, progressively adds participants to the table to enrich the discussion. The idea was to start from a situation (EWE events), find out about best practices (BP) and lessons learned (LL), ask what questions and challenges they raise and boost discussion.

The aim was not to give masterclass presentations but to create a process of interaction and feedback between those who have already faced the problem and those who are trying to come up with innovations.

It progressed as follows:



As the project has a large number of partners, any Questions and Answers (Q&A) that may arise during the process was managed through the WP leaders' interventions or their delegates. In any case, at the end there was an open Q&A turn to address aspects that may have been left pending or not channelled.

- **Participants type**

There were different ways to participate in the discussion:

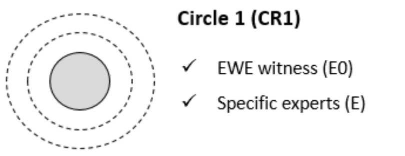
Type	ID	Desired participation	Where does participation take place?	Role
EWE witness	**E0**	In-person	Section 1: CR1,2,3	EWE real cases explanation, BP, LL. Challenges, needs, requirements. Raise awareness.
Invited experts	**E**	In-person	Section 1: CR1	Expertize coming from outside the project worth it to include in the discussion.
WP Leaders	**EP**	In-person	Section 1: CR2,CR3	Discuss IAs, tasks, solutions, etc. Collect WP partners Q&A for CR2. Discussion and Q&A for CR3.
Project partners	**EP**	In-person/ on-line	Section 1: - CR2 through their WP leader - CR3 directly	Discuss IAs, tasks, solutions, etc. Obtained the required framework information for their tasks and IAs.
Invited attendees	**IA**	In-person/ on-line	Section 1: CR3	Q&A if they consider it necessary
Moderators	**M**	In-person	Section 1: CR1, CR2, CR3 Section 2: Mind-map, Table	Moderation + wrap-up
General note-takers	**NT**	In-person	Section 1: all tables	Support for wrap-up Support for guidelines
EWE concepts note-takers	**EWE NT**	In-person	Section 1: all tables Section 2: summary + discussion	Support for EWE definition
Workshop guide	**G**	In-person	Presentation, methodology explanation, agenda, etc.	When necessary.

- **Circles progression**

EWE REAL CASES: Presentation of real cases of EWE.
Description of the event (D1.1, D1.4, IA1.2)
Response in the management of the emergency, why they reacted in that way at that moment (D1.2), how they managed the communication (IA5.9).

BP, LL, KEY MESSAGES:
What was known at the time and what is known now? (D1.1)
Which LL from the previous phenomenon can be applied to the next one?

QUESTIONS, CHALLENGES:
What do we know now (about the phenomenon, emergency management, impact, scenarios in the landscape, etc. covering various scopes of IFM)?
What do we know that we don't know?
Where should we aim for answers to the questions before us?
Science and challenges prioritisation.

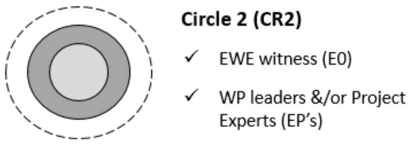


CIRCLE 1:

Discussion E0/E

Pre-established questions were asked by the moderator on the basis of what the participants need to discuss or explain.

The discussion continued among those who have had first-hand experience of the EWE, together with those who are currently working with them on these issues.



CIRCLE 2:

Discussion E0/EP

E0 remained in the table.

External experts (E) abandoned the table and joined the room.

WP leaders (or delegates) joined the table (EPs)

WP leaders who were so far listening to the table (CIRCLE 1) and collecting questions from their team/WP), or whoever they delegate to talk about their IAs, WPs, etc., joined the group.

Questions:

How we can face these challenges and/or solve the doubts that have arisen?

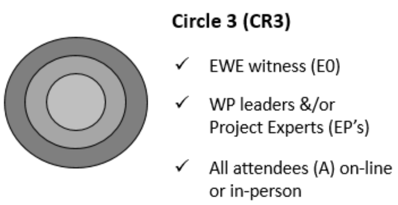
Objectives:

Convert challenges into user-requirements (tools, methodologies, and products).

Guide existing IAs that can provide answers to challenges.

Solve questions and doubts inside the project (=WP leaders).

The members of the group should be informed in advance so that they are prepared to discuss the IAs and solutions, not so that they can present them, but so that they can see where they fit in.



CIRCLE 3:

Discussion E0/EP/rest of attendees:

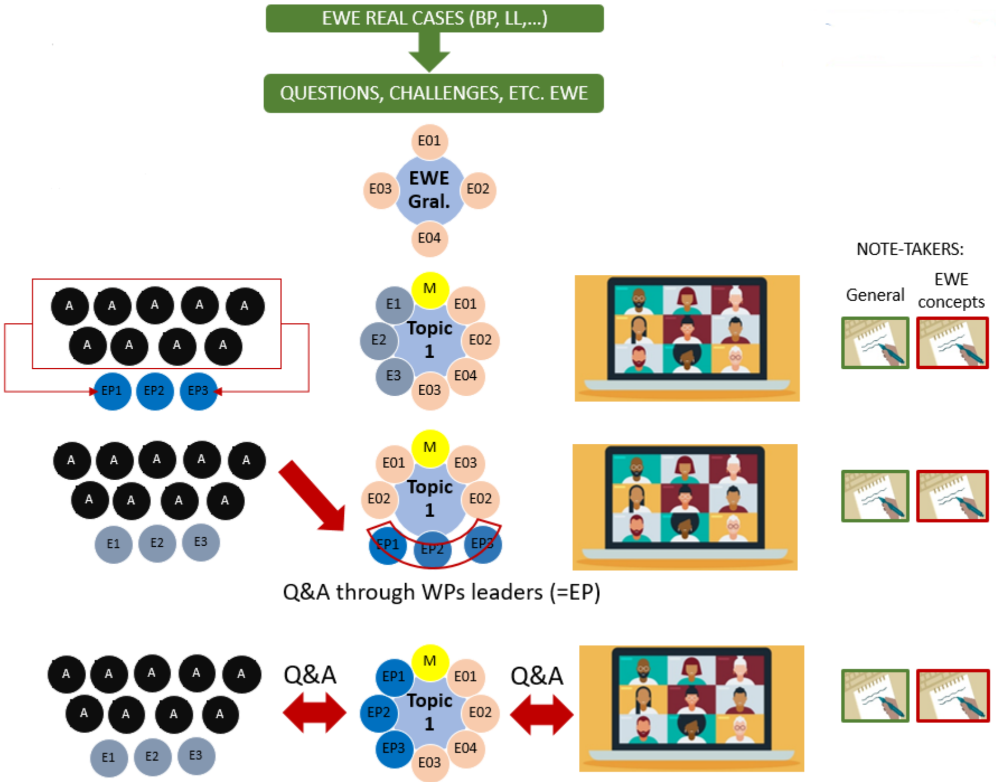
E0 and EP remained in the table and jointly, as a team, they answered and discussed the questions that they have collected on the open Q&A session.

Then an open Q&A session began for questions that had been left unanswered and had not been channelled or that needed to be clarified/given a voice to the person who asked the question:

In-person assistants in the room (microphone in hand)

On-line assistants (via platform)

The following image visually describes the process explained above:

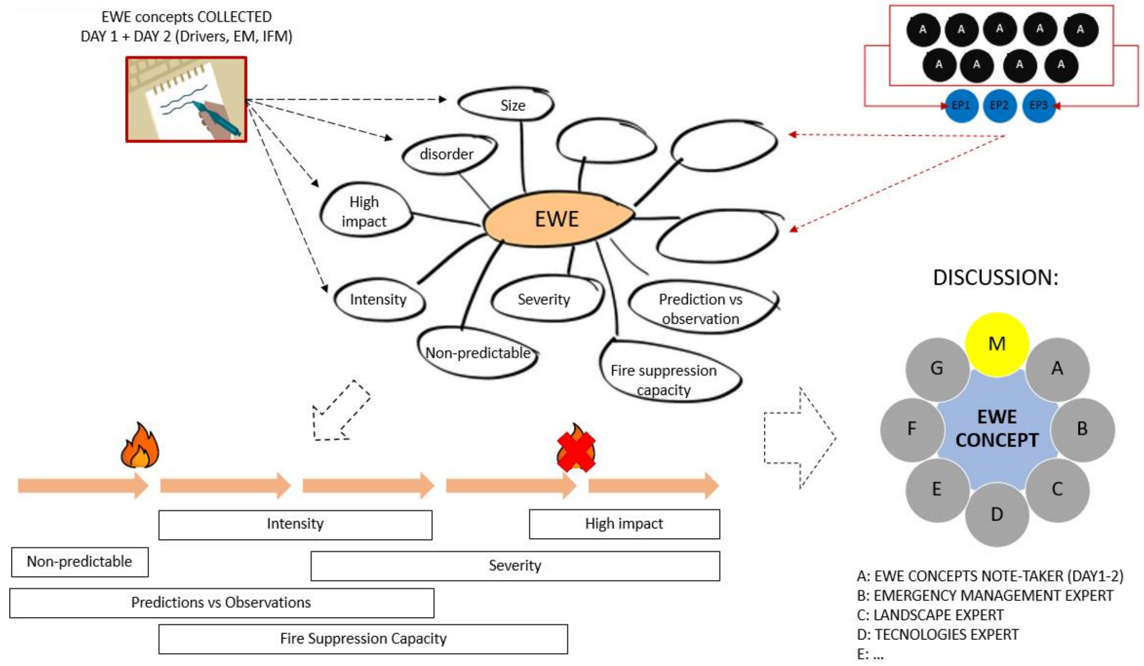


Different note-takers (NT) were also included: 'general note-takers' for wrap-up, guides, moderator, etc. and 'EWE concept note-takers' for section 2.

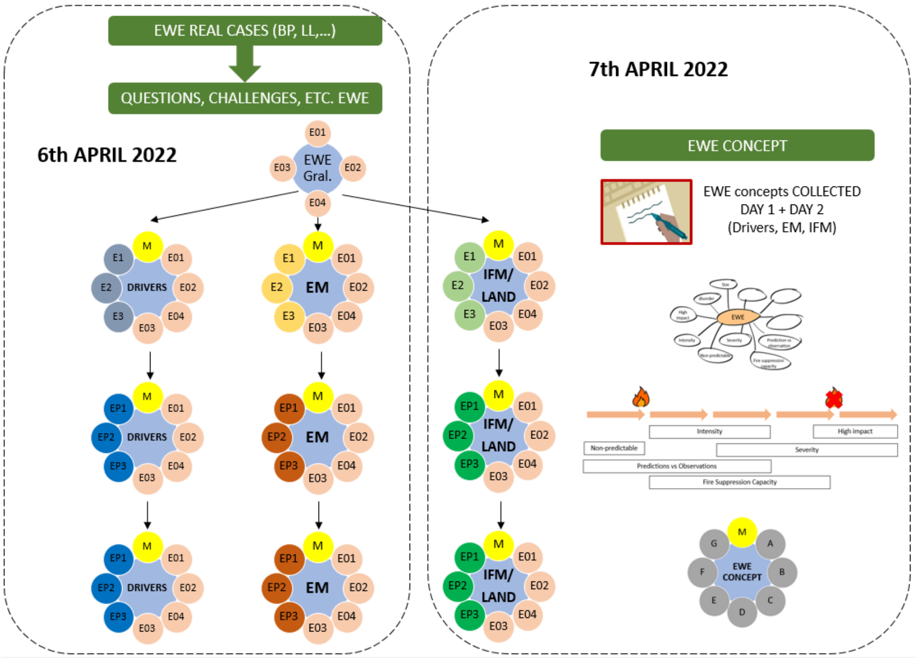
A: Attendees in-person

Methodology Section 2 (Map/Line/Discussion)

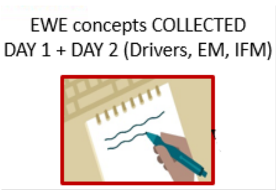
For section 2, the methodology described below was used to arrive at a definition of EWE that works for the project (See next page for more details).



The discussion on concepts did not take place until DAY 2, in order to work on the basis of the discussion on DAY 1. Distribution of the methodologies to be applied between the two days 1 and 2 are described below:

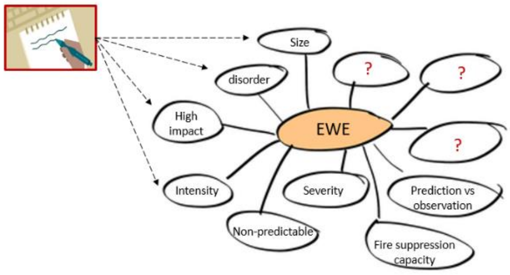


The steps described are visually illustrated below:



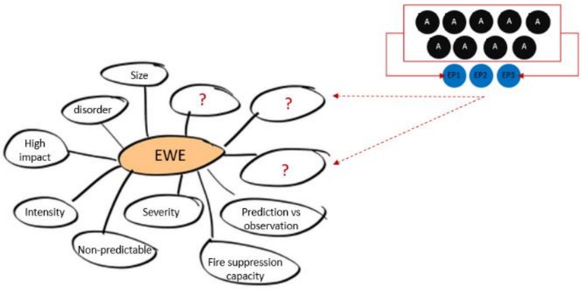
3. **Previous work**: during day 1, all those elements that may refer to the definition of EWE were collected by the EWE concept note-takers (EWE NT). This compilation and

the EWE basic definitions used during the proposal were used as the 'starting point'.



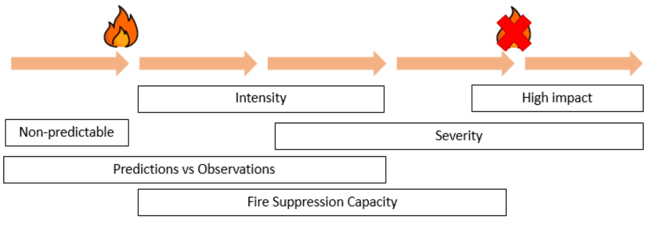
4. **Set-up**: Presentation of what has been collected in day 1 and 'starting point'.

5. **Mind map**: The different concepts linked to the EWE were presented.

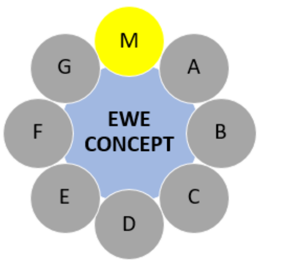


6. **Contributions**: The map was complemented with the contributions that were considered appropriate through the discussion.

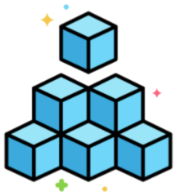
   WP leaders (or their delegates) collected input from their WPs and acted as representatives.



7. **Line of definitions**: Often, a definition may not suit us if the language used, if it is not our own or refers to concepts that are far from our field of expertise. Then, maybe it would be possible that the different ways of defining EWE also correspond to different moments or phases, areas, thematises, etc. Therefore, we proposed to use a line with these different phases (or similar concepts) in which the different ways of defining EWE from the different fields are identified.



8. **Table of discussion**: Once the conceptual map and the conceptual line had been drawn up, they were discussed in a work group to arrive at a common definition for the project, which may have specificities for each area. It was noted, that the discussion group should be sufficiently cross-cutting to be able to discuss the definition from sufficient ambits, with a willingness to integrate and a broad perspective, but without forgetting that EWE has different characteristics from those we already know and can/know how to deal with.



AGREED DEFINITION

9. **Agreement**: Finally, an agreed definition will be developed.

Workshop 2

Objective

The goal of the workshop was to reach a common understanding (or even a working definition) of what "fire resilient landscapes" are. The idea was to identify lessons learned regarding this concept from different perspectives and broadly define challenges of designing resilient landscapes to wildfires and EWE.

Methodology

The methodology was based on the fact that there are many dimensions under which fire resilient landscapes can be evaluated, so various topics related to fire resilient landscapes were identified to cover as many dimensions as possible.

1. *Selection of the topic and subtopics*

The selection of topics was based on the discussion held at two internal meetings with the leaders of the different subtasks of WP1. The topics selected were ecology and landscape management, fire as a management tool, economics, and governance and risk awareness (Box A2) to cover a wide range of dimensions. In the case of ecology and landscape management and the fire as management tool topic, different subtopics were also identified (e.g., fire as a management tool, differentiated into traditional burning, prescribed burning, and let-it-burn).

Box A2 Topic discussed during the workshop on fire resilient landscapes.

Topic 1. Ecology and landscape management

Discussions about fire ecology, wildfire scenarios, forest and landscape management for fire risk reduction, adaptive management, ecosystem services integration on forest planning, wildland urban interface resistant design, or post-fire restoration were proposed.

Topic 2. Fire as a management tool

The effectiveness, constraints, and challenges of the use of fire to create fire resilient landscapes were considered as potential themes to be discussed. Three different uses of fire were thought to be addressed: traditional, prescribed, and managed fires (‘let it burn’ or ‘resource objectives wildfires’).

Topic 3. Economic aspects of resilient landscapes

The topic session discussion was thought to be about the need for mechanisms that use efficiently the scarce resources while simultaneously maintaining a desirable level of ecosystem services and reduce the likelihood of future losses. The discussions were conceived to address economic variables shaping fire resilience and the design and constraints/challenges of economic instruments (indirect/value chain-oriented or direct/incentive schemes) for facilitating the viability of the resilient landscapes.

Topic 4. Governance and risk awareness

Issues regarding the need of collaborative and systemic risk governance for dealing with, achieving, managing, and maintaining more fire resilient landscapes across rural Europe are thought to be addressed. Governance and risk awareness were considered to be approached from the following perspectives: stakeholders' engagement, institutional wildfire risk management and planning, and the planning and governance process itself. Risk culture and awareness was brought to the discussion by exploring the landscape social dimension focusing on fire culture, vulnerability and resilience.

2. *Structure of the topic sessions*

The general structure of the workshop consisted of various presentations given by external or internal experts (keynote speakers) on each topic to facilitate the initiation of the discussion between participants. Each presentation was followed by a two-way discussion and questions with the FIRE-RES partners responsible for the corresponding activities (about 2.5 hours per topic). The roles of the people involved in the workshop are shown in Box A3.

For each topic and subtopic (if any), a 20-minute presentation was scheduled for each keynote speaker. Keynote speakers were asked to answer/approach the following questions during their presentations:

1. From the perspective of your topic/sub-topic, what factors/dimensions/components are fundamental to promoting, implementing, and sustaining resilient landscapes?

2. What do you see as the main difficulties, gaps, and opportunities in these factors?

Box A3. Workshop roles and responsibilities

Topic organizer: contacted and invited the internal or external experts on each of the selected topics or subtopics and structured the topic discussions.

Moderator: each topic was led by a moderator who framed the session and facilitated the discussion.

Note-taker: documented the results of the workshop. There was a note taker for each topic.

3. Miro board session

With the goal of incorporating all project members' ideas about fire resilience landscapes, the Miro board tool was used. The Miro board is a collaborative digital whiteboard that can be used for research, ideation, brainstorming, mind mapping, and a variety of other collaborative activities. Using this tool, FIRE-RES members were encouraged to contribute their ideas about what a fire resilient landscape is from their own perspective prior to the workshop. At the end of the workshop, the Miro board was revised to incorporate the new information gathered during the workshop and the main ideas presented. The Miro board session facilitated work on developing a common conceptual framework for the project.

List of figures

List of tables

FIRE-RES